Cenozoic inversion structures in the foreland of the Pyrenees and Alps

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ABSTRACT

Southeastern France forms the foreland of the Late Cretaceous to Paleogene Pyrenean and the Cenozoic Alpine orogens. Unlike other thrust belts, neither the eastern parts of the Pyrenees in Languedoc and Provence nor the Western Alps are associated with major flexural foreland basins. Instead the area is characterised by a complex array of multi-directional compressional foreland structures.

These foreland structures developed in response to Pyrenean and Alpine compressional and transpressional reactivation of pre-existing tensional and transcurrent crustal fault systems which delimit extensional sedimentary basins ranging in age from Permian to Oligo-Miocene. These basins developed during the Permo-Carboniferous collapse of the Hercynian orogen, the Mesozoic Tethyan rifting phase and the Eo-Miocene development of the West-European rift system. Crustal shortening achieved during the inversion of these basins is locally rooted in the basement and possibly translated via a lower crustal detachment level into the respective orogens.

Due to the intensity of these foreland deformations, and partly also due to their superimposition, the Pyrenean and Alpine thrust fronts are poorly defined and in large areas diffuse. Although remnants of a Paleogene flexural foreland basin are locally preserved, this basin, which had presumably limited dimensions, was largely destroyed in conjunction with the inversion of Permian, Mesozoic and Cenozoic tensional structures. In addition, the passive margin sedimentary prism of the Gulf of Lions, which opened in Early Miocene times, conceals part of the Pyrenean fold belt.

In order to gain a better understanding of the evolution and deep architecture of some of the observed foreland structures, surface and sub-surface geological data were integrated and compared with the results of sand-box analogue models that were monitored by X-ray tomography. The kinematics of basin inversion are discussed in an evolutionary framework that is characterised by repeatedly changing stress regimes.

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1 INTRODUCTION

Fold-and-thrust-belt foreland systems are usually characterised by a wide flexural basin (Beaumont, 1981), which develops in the autochthonous foreland in front of a composite tectonic wedge made up of various allochthonous thin-skinned and basement-involved units. Simultaneously, the surface topography of the wedge itself tends to reach an equilibrium, characterised by a specific taper (Dahlen et al., 1984). This is not the case in Provence and Languedoc, as the Pyrenean and Alpine thrust fronts, well expressed in the morphology of the Pyrenees to the West or in the northern part of the Western Alps, become progressively cryptic in the basin of southeastern France (BSEF).

In fact, due to strong Hercynian and Tethyan tectonic inheritance, numerous pre-existing extensional structures were reactivated and inverted during Paleogene and Neogene compressional phases, the orientation of reactivated structures being at any time directly controlled by the direction of the prevailing horizontal compressional stress axis. The occurrence of basement-controlled inversion structures accounts for the abnormally high elevation of isolated structures in the foreland, far from the thrust front.

Inversion tectonics were recognised for a long time in the Pyrenean and Alpine orogens (Lemoine et al., 1981; Mugnier et al., 1987; Gillcrist et al., 1987; Graciansky et al., 1988; Gratier et al., 1989); however, their study was mainly restricted to the allochthon, where the initial relationships between the basement and its sedimentary cover are unfortunately no longer preserved. Because of the great variability in the timing and trends of both extensional and compressional episodes, Languedoc and Provence constitute a famous tectonic province, studied since the early days of the structural geology (Lutaud, 1935, 1957; Goguel, 1947, 1963; Aubouin and Mennessier, 1960; Ellenberger, 1967; Mattauer, 1968; Lemoine, 1972; Aubouin, 1974). It is indeed a key area for the study of foreland inversions, in which very contrasted boundary conditions resulted in quite distinct tectonic features.

This paper aims at documenting the role of inversion in the development of some classical structures of Provence and Languedoc. Analogue models of tectonic inversions will also be confronted with regional surface and subsurface data to provide additional constraints when connecting shallow geometries with the poorly imaged basement architecture.

2 REGIONAL GEOLOGICAL BACKGROUND

Detailed regional syntheses dealing with the geology of the basin of southeastern France (BSEF) were published by Baudrimont and Dubois (1977), Debrand-Passard et al. (1984) and Roure et al. (1992, 1994). Therefore, only major tectono-sedimentary episodes will be discussed in the following.

2.1 Late Hercynian Collapse and Permo-Carboniferous Basins

Recent deep seismic profiling across the Biscay and Aquitaine domains have imaged south-verging Hercynian thrusts and overlying post-nappe Permian basins (Fig. 3a; Choukroune et al., 1990). Simultaneously, new field work, petrographic and microtectonic studies on the fabric and transport direction (kinematics) of Late Paleozoic sedimentary or metamorphic units, forming the southern part of the Massif Central (i.e. Montagne Noire; Burg et al., 1990; Echter and Malavieille, 1990; Van den Driessche and Brun, 1991), have greatly improved our knowledge of the West European Hercynian tectonic edifice. Following the last compressional episodes during the Carboniferous, the Late Hercynian deformations reflect the general collapse of the pre-existing orogen, as evident from two distinct types of structures:

(1) high angle intra-crustal strike-slip faults, trending north or northeast, such as the Sillon Houiller and Cévennes Fault (Fig. 1), are identified in the French Massif Central and in Languedoc (Arthaud and Mattauer, 1969),

(2) eastwards trending normal faults, which controlled the development of Late Carboniferous and Permian extensional basins (Ste. Afrique, Rodez or Lodève in Languedoc; Figs. 1 and 8a; Santouil, 1980; and Le Luc in Provence; Toutin-Morin and Bonijoly, 1992; Figs. 1 and 9a).

Although these Late Paleozoic basins are well exposed along the western (Massif Central) and eastern (crystalline Provence and Belledonne Massif in the Alps) borders of the BSEF, their subsurface extent in Languedoc and Provence remains highly conjectural. Nevertheless, exploration wells have revealed extensive Permian sequences north of the Pic-St. Loup structure in Languedoc (Roure et al., 1988; Figs. 1 and 8a), and Paleozoic sequences occuring beneath the Arc syncline, south of the Ste. Victoire structure in Provence (Tempier, 1987; Biberon, 1988; Figs. 1 and 9a).

Seismic profiles along the western border of the BSEF, have also imaged extensive Carboniferous strata. Recently cored during scientific drillings (GPF program; Giot et al., 1991; LeStrat et al., 1994), these Carboniferous strata, especially the coal measures, constitute potential detachment levels which were activated at least locally during Jurassic and Oligocene extensional phases (Roure et al. 1992, 1994; Bonijoly et al., 1995; Fig. 2).

Finally, exploration wells drilled in the Jura Mountains of France and Switzerland also identified Carboniferous strata in a subthrust position beneath the folded Mesozoic series (Laubscher, 1986; Noack, 1989; Mascle et al., 1994; Philippe, 1994). Reflection seismic profiles on the eastern border of the Jura also revealed inverted Permo-Carboniferous basin (Gorin et al. 1993, Signer and Gorin, 1995).

2.2 Tethyan Rifting and Intra-Mesozoic Detachment Levels

After local evidence of Early Triassic extension, the main Tethyan rifting episode occurred in Late Triassic and Liassic times (Lemoine and Trümpy, 1985; Graciansky et al., 1988; Elmi, 1990; Bergerat and Martin, 1993, 1995). This is demonstrated by the strong subsidence of the BSEF at this time, and by rapid Liassic facies and thickness changes, which were controlled mainly by the activity of major northeast-trending normal faults (Elmi et al., 1991; Giot et al., 1991). Recent reflection seismic profiles confirmed that only few of the Jurassic faults involves the infra-Triassic basement (i.e. the Cévennes, Nîmes and Durance faults, Fig. 1), whereas most of the other structures are detached in Triassic evaporites (Petit et al., 1973; Roure et al., 1988, 1992).

Block faulting ceased during the Middle Jurassic, as attested by the regional Dogger unconformity, which marks the onset of the post-rift thermal subsidence of the BSEF (Figs. 2 and 12).

However, due to the contrasted paleobathymetries, platform conditions prevailed until the Lower Cretaceous (i.e. Aptian Urgonian platform) in Languedoc and Provence in the south, as well as in the Vercors and the Jura Mountains in the north. On the contrary, basinal conditions and deposition of thick, ductile black-shales (the Liassic to Oxfordian "Terres Noires") occurred in the intervening Vocontian Trough (Fig. 13a), where effectively only the Late Jurassic sequence is made up of brittle carbonates (Tithonian deep-water carbonates and breccias; Fig. 2).

Potential décollement horizons occur, apart from Triassic evaporites, in the Jurassic and/or Lower Cretaceous shales. Nevertheless, due to rapid lateral facies and thickness variations, these potential detachments horizons are rather discontinuous, especially at basin-to-platform transition zones. As a result, the most complex structural Cenozoic configurations are found in these areas (Figs. 2 and 13).

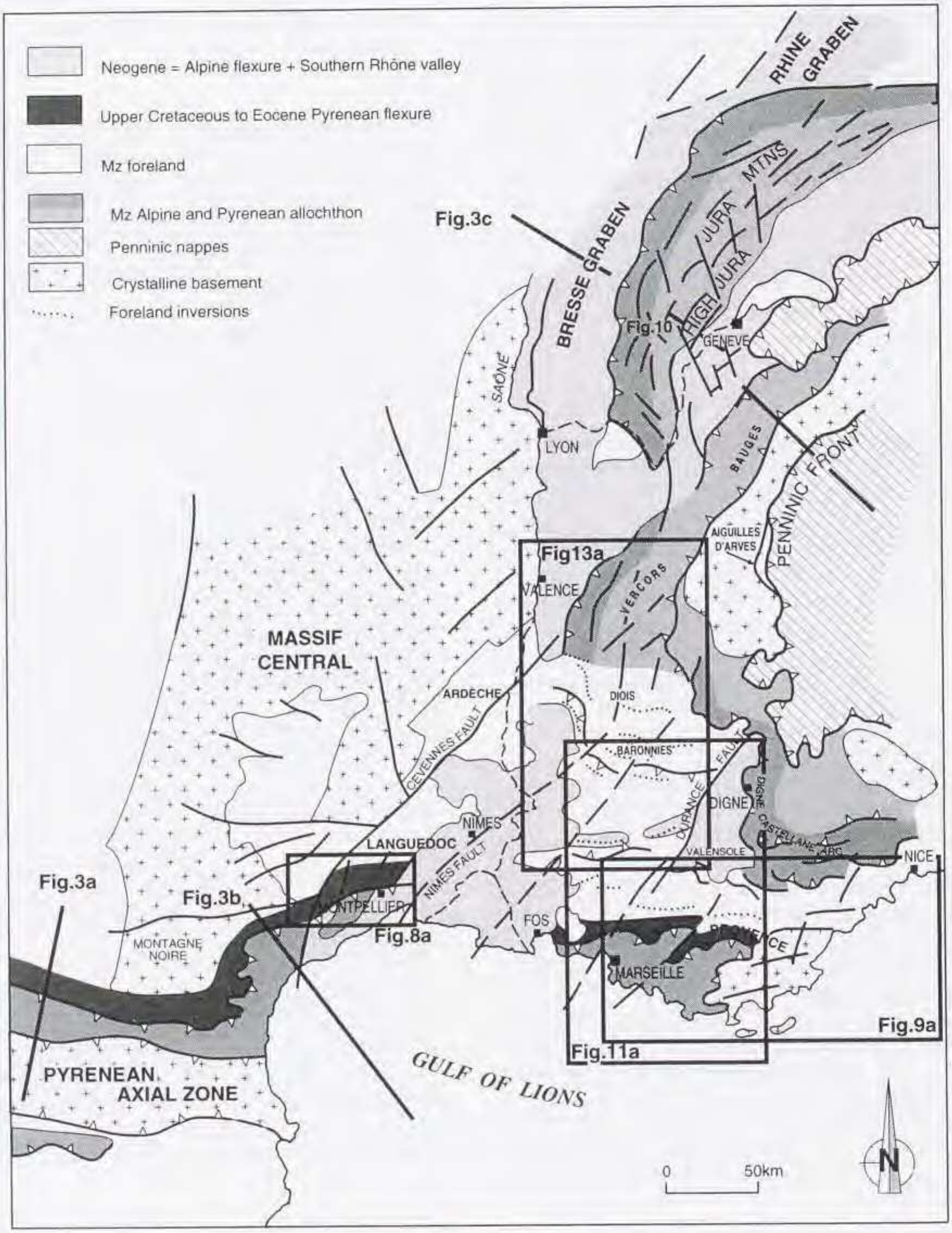

FIG. 1. Structural framework of the basin of southeastern France outlining the Pyrenean and Alpine frontal thrusts.

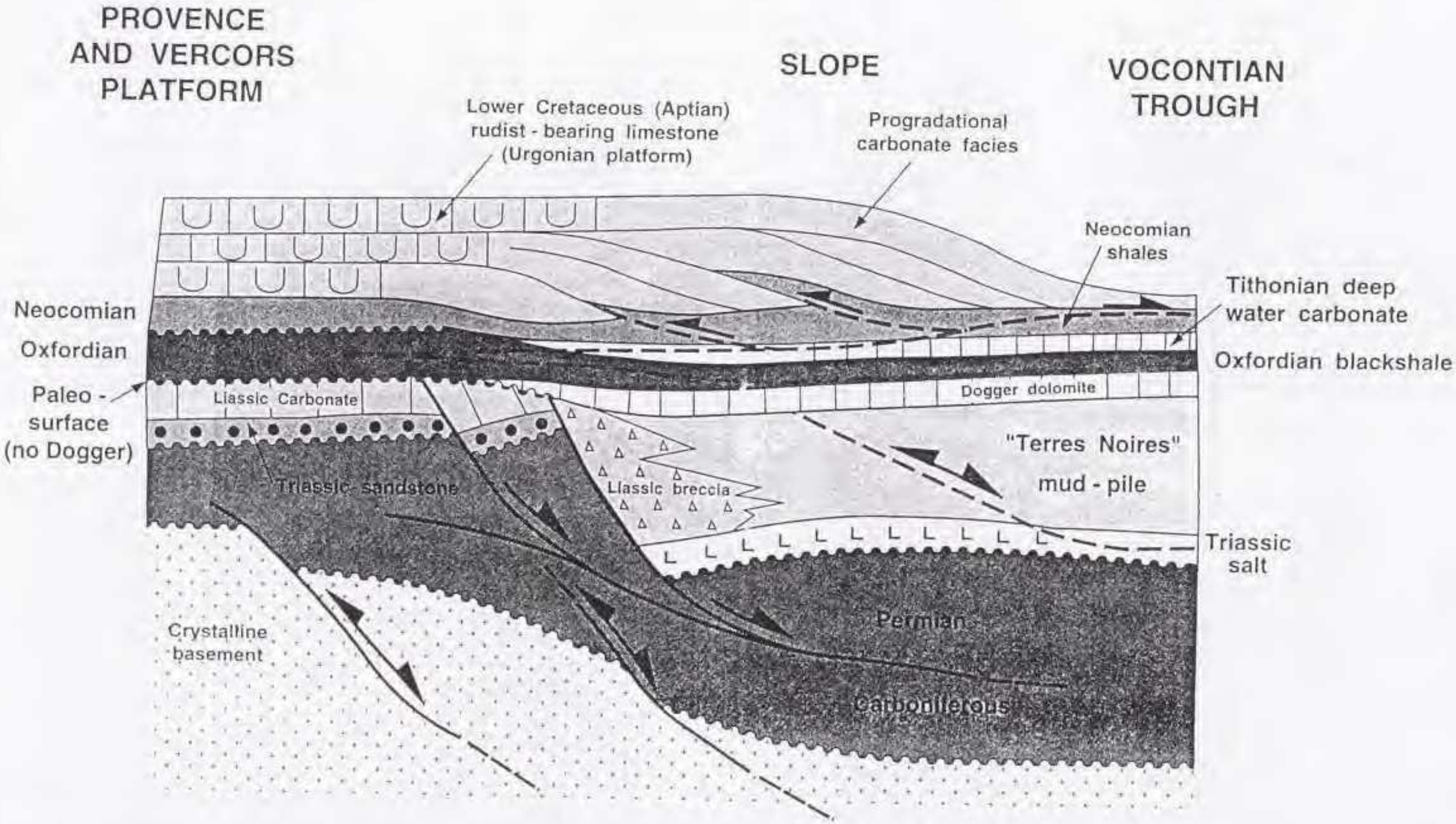

FIG. 2. Lithostratigraphic diagram showing lateral sedimentological variations in the location of potential detachment horizons.

the La Nerte-Ste. Baume structure as representing the easternmost part of the Pyrenean frontal overthrust. Accordingly, all the surface structures identified further north (Alpilles, Luberon, Ste. Victoire, La Lance and Ventoux-Lure east-trending structures; Fig. 11a) are interpreted as basement-controlled inversion features which are connected with the Pyrenean thrust front.

Further east and northwards, i.e. in the Annot area, in the Aiguilles d'Arves or Bauges massifs (Fig. 1), the Alpine allochthon itself also provides evidences for Paleogene deformations and the development of an early flexural basin. The Priabonian succession, which disconformably rest on Cretaceous carbonates, is now entirely incorporated into the Alpine tectonic edifice and comprises shallow-water nummulite-bearing carbonates that grade upwards into pelagic marls and deep-water turbidites. As such, they outline the rapid subsidence of the European foreland in front of advancing nappes (Vially, 1994).

2.3.2 Oligocene Extension and Stress Permutations

Widespread extension occurred in western Europe during Oligocene times, leading to the development of the West European Rift system, extending from the Netherlands and Germany (Rhine Graben) to the Mediterranean (Bresse Graben, Limagnes, Rhône Valley and Camargue).

In the south, rifting progressed to crustal separation, thus inducing the opening of the oceanic Gulf of Lions and consequently, the building up of a classical passive margin during the Neogene, off the Languedoc and Provence coasts of the West Mediterranean Basin (Burrus, 1989; Gorini et al., 1993). During the extensional process, numerous Pyrenean thrusts were reactivated (negative inversion), especially south of St. Chinian (Fig. 3b; Gorini et al., 1991; Roure et al., 1994).

Because of important syn-rift and post-rift subsidence of the area, the former Pyrenean structures are no longer preserved at the surface near the Rhone Delta, thus impeding a direct structural correlation between Provence and Languedoc (Fig. 1).

The paleostress regime remained relatively consistent during the Oligocene, with an overall N110 trend for the minimum principal horizontal stress trajectories (Bergerat, 1985; Villéger and Andrieux, 1987). Detailed microtectonic analyses outline a progressive permutation of the principal stress axes during the transition from the Eocene to the Oligocene (Pyrenean compression with a N0 to N10-trending sigma1 and Oligocene extension, with a N110-trending sigma3). Similarly, a progressive change of extensional stress axes from N110 to N155 is evidenced during the Oligocene in the Marseille Basin (Hippolyte et al., 1993), prior to the onset of the Neogene Alpine deformations.

During Oligocene times, major northeast-trending Late Hercynian basement structures were reactivated (Cévennes, Nîmes and Durance faults; Figs. 1 and 11a). Moreover, the Triassic detachment level was also reactivated as indicated by numerous Oligocene normal faults which are restricted to the Mesozoic sediments and thus have a listric shape (Fig. 1; Roure et al., 1988, 1992); the Alès basin also developed in a piggyback position above the intra-Triassic décollement.

2.3.3 Alpine Compression and its Sedimentary Record in Southeastern France

Alpine compressions occurred during the Neogene, with a progressive change in the orientation of sigma1 (from N20 to N90 or N120; Bergerat, 1985; Villéger and Andrieux, 1987).

The Alpine thrust front is well defined in the Digne and Castellane arcs (Figs.1 and 9a). West of Digne, it is bordered by the autochthonous flexural Miocene molasses of the Valensole Plateau (Dubois and Curnelle, 1978). Similarly, from the Vercors to the Jura Mountains, the Alpine thrust front can be accurately traced and is also bordered by marine sediments deposited in a Miocene flexural basin (Figs. 1 and 3c; Mugnier and Viallon, 1984; Gratier et al., 1989; Guellec et al., 1990a, 1990b). However, in the intervening area, i.e. between the Drôme River to Digne (i.e. in the Vocontian Trough; Figs. 1 and 13a; Goguel, 1963; Gratier et al., 1989), neither the Alpine thrust front

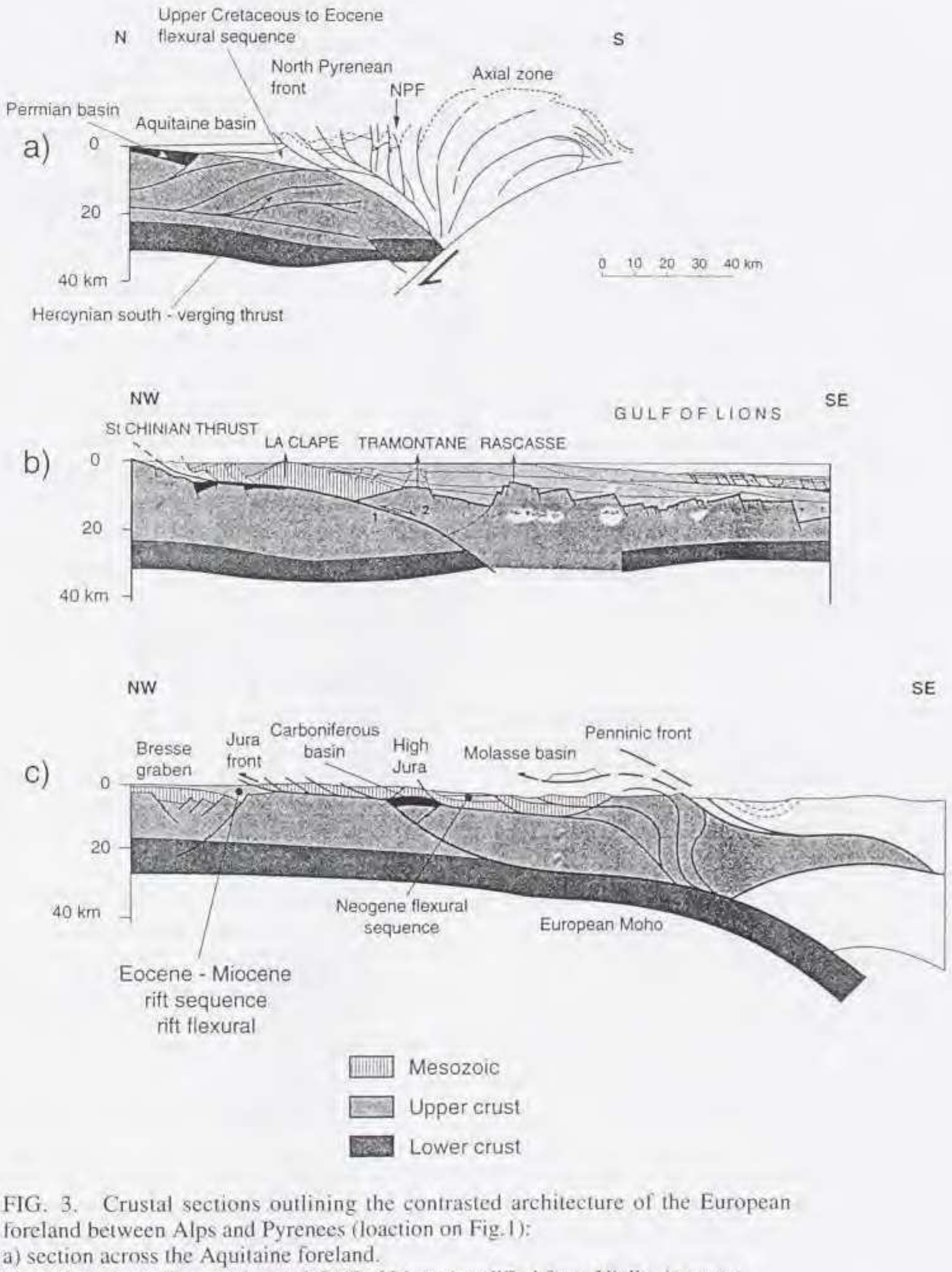

FIG. 3. Crustal sections outlining the contrasted architecture of the European foreland between Alps and Pyrenees (loaction on Fig.1):
a) section across the Aquitaine foreland.
b) section across Languedoc and Gulf of Lions (modified from Vially, in prep.)
c) section across the Alps and Jura Mountains.

2.3 Kinematics and Timing of the Pyrenean and Alpine Deformations

Recent deep reflection seismic profiles imaged the entire crust of the European foreland beneath the North Pyrenean (Choukroune et al., 1989) and Western Alpine (Guellec et al., 1990a, 1990b) thrust fronts, outlining the gentle flexure of the underthrusted lithosphere, and the development of a subaerial accretionary wedge and adjacent flexural basin (Figs. 3 a, c).

Because of its multistage tectonic history, with interferences between Pyrenean or Alpine compressional structures and Oligocene rifting, the BSEF hardly compares with typical foreland basins. Even the Pyrenean and Alpine thrust fronts become diffused in this area, and special attention is required to trace them with some confidence.

2.3.1 Pyrenean Compression and its Sedimentary Record in Languedoc and Provence

Although Late Cretaceous compressional deformations induced in Languedoc and Provence local erosion and deposition of tectonic breccia at the leading edge of early structures (i.e. Ste. Victoire; Lutaud, 1935, 1957; Tempier and Durand, 1981), most of the Pyrenean shortening occurred in Eocene times. However, microtectonic evidences in continental conglomerates in Languedoc indicate that compression persisted during the Lower Oligocene in Languedoc.

The Eocene stress field was remarkably stable in the entire European foreland and was characterising a north-trending maximum horizontal compressional stress trajectory (Bergerat, 1985).

West of the Rhône River, the North Pyrenean thrust front is still relatively easy to trace in Languedoc. Late Cretaceous to Eocene continental sequences progressively onlap the basement of the Massif Central north of the Pyrenean thrust front (Ellenberger, 1967; Figs. 3b and 4). Younging progressively northwards, this flexural sequence is partly underthrust beneath or even accreted to the Pyrenean allochthon (Figs. 3b and 4; Roure et al., 1988).

Eastwards, the Pyrenean thrust front continues into the Montpellier overthrust, which, based on well results, was transported a minimum of 8 km to the north (Andrieux and Mattauer, 1971). Moreover, there is local evidence for Eocene transpressional reactivation of such major northwest trending Late Hercynian structures as the Cévennes Fault in Languedoc (Arthaud and Mattauer, 1969), and the Durance Fault in Provence.

In Provence, however, the conditions are more complex. Despite the widespread occurrence of Paleogene north- and south-verging compressional structures, many authors proposed a complete decoupling of the Mesozoic sedimentary cover from its basement, and very large amounts of shortening (Guieu and Rousset, 1980; Tempier, 1987; Biberon, 1988; Deville et al., 1994). However, as discussed in the following, most structures, even some of those verging towards the north, are better interpreted as basement-controlled inversion features; this concept precludes a general detachment of the Mesozoic sediments from their basement.

In fact, only two north-verging structures can be traced over large distances and have a regional lateral extent (Fig. 9a):

(1) in the south, the Cap Sicié basement overthrust relates to a shallow-dipping detachment that is related to the Pyrenean allochthon,

(2) immediately to the north, La Nerte and Ste. Baume thrusts are two contiguous thin-skinned structures, which only involve Mesozoic sediments, and are thrust over the Late Cretaceous to Eocene continental deposits of the Arc syncline (Aubouin and Chorowicz, 1967; Carrio-Schaffhauser and Gaviglio, 1985). Both, the age of the sedimentary infill and the structural position of the confined Arc basin, compare adequately with the coeval flexural sequence of the limited Pyrenean foreland basin, as already identified in Languedoc (Figs. 1 and 3a).

Because no other continuous north-verging structure occurs farther to the north, we consider

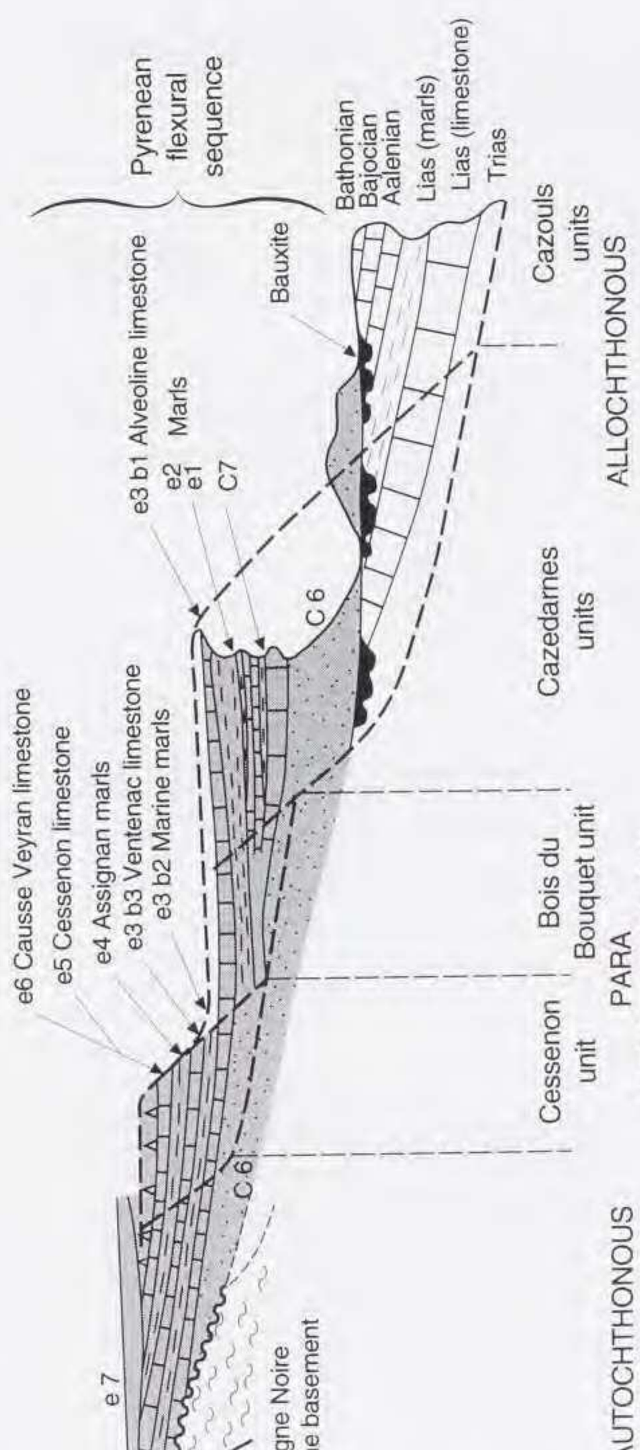

FIG. 4. Schematic diagram outlining the progressive onlaps of the Late Cretaceous to Eocene Pyrenean flexural sequence near St. Chinian.

nor the Miocene flexural basin can readily be identified. This is due to the inversion of the Vocontian Trough, containing a thick Jurassic basinal sequence, during the Pyrenean and Alpine episodes of crustal shortening; the resulting structural relict, that undoubtedly was already initiated during the Late Cretaceous to Eocene Pyrenean orogeny, precluded the development of a Miocene flexural depocentre in this part of the European foreland.

Miocene marine deposits occurring in the Valreas Basin west of the basement-controlled Vocontian inversion structure (Figs. 1 and 13a), are underlain by a stable structural domain, corresponding to the Urgonian carbonate platform, which was unaffected by the foreland inversion movements. There, Miocene molasse deposits can be interpreted either as representing the outermost onlapping sequence of the Neogene foredeep, or preferentially as having accumulated in a post-rift thermal subsidence basin, that is related to Oligocene extensional structures; the latter accounts for the geophysically defined crustal thinning evident in this portion of the foreland (Ménard, 1979; Hirn et al., 1980).

3 SCALED-DOWN MODELS OF BASIN INVERSION

Sand-box experiments are frequently used to study the incidence of various parameters during basin inversion processes (McClay, 1989; Buchanan and McClay, 1991). However, recently developed computerised X-ray tomographic conservative techniques permit, at any time of the ongoing experiment, a better imaging of incremental deformations and the documentation of the spatial architecture of the model in any direction, without having to destroy it (Colletta et al., 1991).

This technique has been applied at the IFP to study the boundary conditions of structural inversion. Thus, during a systematic set of experiments, either the basal friction, the number and the location of ductile interbedded layers, the attitude of the pre-existing basement faults and the orientation of the maximum compressional stress axis, were modified (Sassi et al., 1993). Some of these experiments, especially those dealing with oblique inversion, were successful in modelling the evolution of the Saharan Atlas (Vially et al., 1994).

Below we present some of the results of such model experiments which can be compared with the regional inversion structures occurring in the BSEF, and provide additional constraints to support new hypotheses on the deep architecture of these structures, particularly concerning the basement-cover relationship (Roure et al., 1992, 1994).

3.1 Extensional Listric Growth-fault Structure and its Subsequent Inversion

A first experiment attempted to simulate the structural inversion of a basin controlled by a listric growth fault (Fig. 5; see Roure et al., 1992 for details of the apparatus). The hanging-wall was maintained rigid during the compressional deformation of this model, whereas a Mohr-Coulomb behaviour was assumed for the foot-wall. The geometry of the listric fault, as determined by the shape of the rigid hanging-wall, was therefore fixed during the entire experiment. A total decoupling between hanging-wall and foot-wall was made possible.

During the initial extensional process, an asymmetrical half graben and a conventional rollover structure, with a crestal collapse graben and numerous normal faults, was generated in the foot-wall (Fig. 5). Simultaneously, the topography of the model was preserved horizontal, by progressively filling in the developing depressions with sediments.

In a second stage, incremental shortening was applied to the model in an effort to restore the mobile foot-wall to its initial preextensional position. The resulting geometry indicates that normal faults in the roll-over crestal collapse graben are not reactivated, but act as the roots for newly developing reverse faults during the first stage of shortening.

As discussed below, this mode of deformation can be compared with regional examples along the Durance Fault, which effectively outlines syn-extensional Oligocene growth strata above an

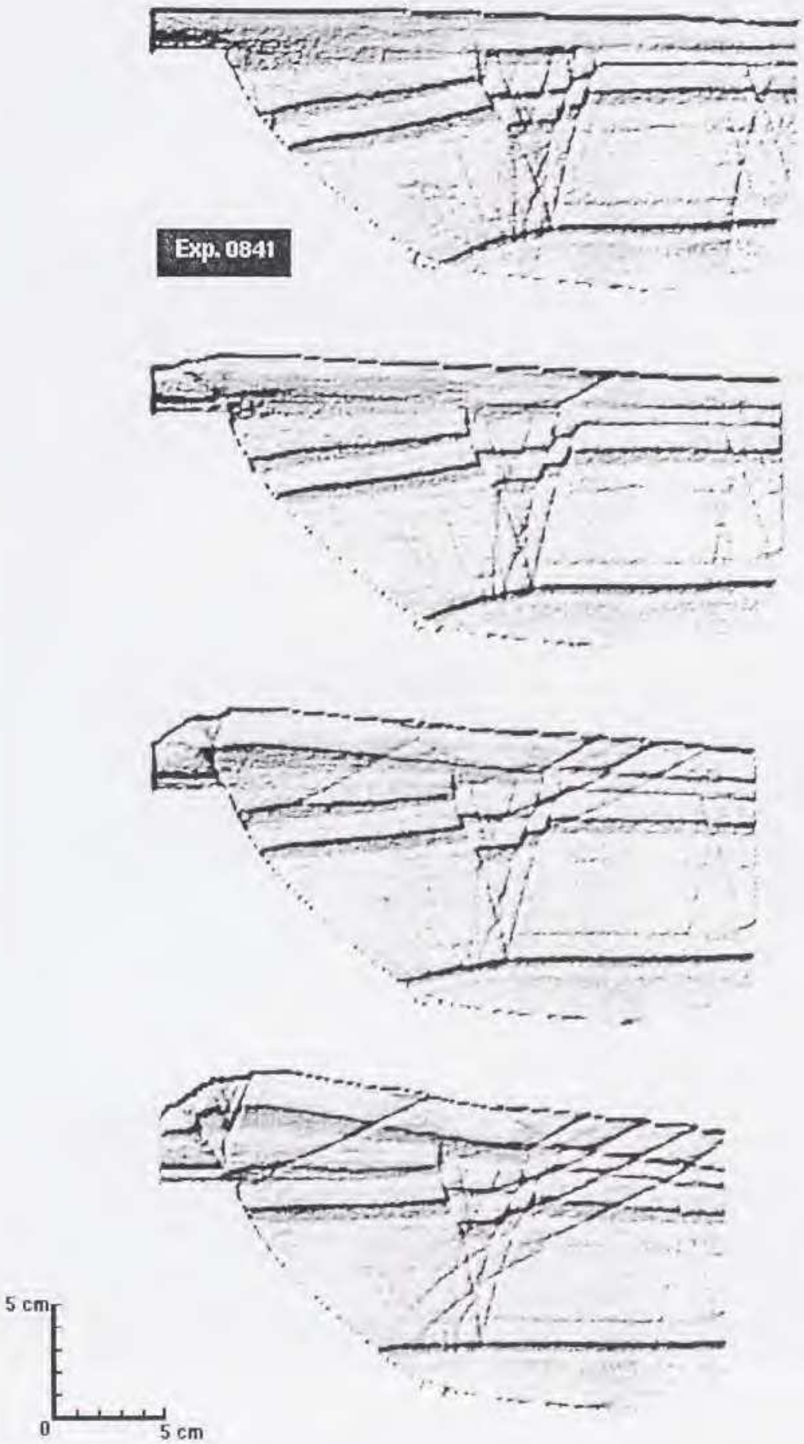

FIG. 5. X-ray images of sand-box experiment simulating the tectonic inversion of a hangingwall block controlled by a normal listric growth fault. Note the nucleation of reverse faults at the tip of normal faults bounding the crestal collapse graben.

intra-Triassic detachment that developed along the trend of a high-angle basement fault (Fig. 11b). Unfortunately, the present apparatus does not permit a coeval reactivation of the basement high-angle fault in the hanging-wall. Nevertheless, as shown by the results presented, additional vertical motion of the basement would mainly result in an overall increase of the footwall culmination, and would have only a minor effect on the internal geometry of the foot-wall block, due to accommodation of these motions along the listric detachment fault.

3.2 Multilayer Sand-cake, Basement Short-cut and Wedging

Another set of experiments aimed at evaluating basin inversion in a multi-layer sand-cake with a pre-existing high-angle basement fault (see Roure et al., 1994; Vially et al., 1994 for a precise description of the apparatus). For this study, a rigid basement was decoupled along a mobile high-angle fault plane, and sediments were deposited horizontally on both the hanging-wall and foot-wall sides of the model. A vertical offset was preserved between alternating brittle and ductile materials in the sedimentary cover of the basement in an attempt to simulate the presence of a pre-existing normal fault in the sediments. Only the shallowest brittle horizon was deposited over the entire model, across the now inactive normal fault, thus simulating the post-rift sequence (Figs. 6 and 7).

In a first set of experiments (Fig. 6), orthogonal compression was applied to the entire footwall, permitting simultaneous incremental vertical motions along the basement fault. As a result, the sedimentary infill of the basin was gradually inverted, with deformations being guided by a forced motion along the rigid hanging-wall basement block.

However, as predicted by mechanical studies on fault reactivation (Jaeger and Cook, 1969; Sibson, 1985), the free upper portion of the pre-existing normal fault is not reactivated in the sedimentary cover during this process of orthogonal inversion, but is rather passively transported above a newly created low-angle fault which splays upwards from the rigid basement, thus outlining a typical short-cut geometry (Huygue and Mugnier, 1992; Fig. 6). At the same time, a triangle zone (fish-tail) develops, with the deep short-cut block progressively wedging out the brittle cover of the hangingwall, inducing the development of a backthrust.

By slightly modifying the boundary conditions in the shallow horizons (i.e. the lateral extent or the location at depth of the ductile horizons), it is possible to generate non-cylindrical structures, characterised by shallow thrusts which accommodate main transport out of the basin (same dip attitude as the deep high-angle basement fault) or into the basin (shallow conjugate backthrusts). Double vergence pop-up structures may indeed occur in the transition zone between these two asymmetric domains when they develop along trend of the same pre-existing basement fault (Fig. 7).

In a second set of experiments, oblique compression was applied to the same initial geometry. In these models, horizontal sections display predominantly en-echelons structures in the sedimentary layers, with crestal collapse fractures developing in inversion-related anticlines, obliquely to the trend of the pre-existing basement fault. Under transpressional conditions, reactivation of the shallow and free portion of the pre-existing high-angle normal fault becomes possible, with no systematic development of newly created low-angle faults and short-cuts.

4 LATE HERCYNIAN INHERITANCE AND CENOZOIC INVERSIONS

In the following, we compare structures observed in the BSEF with results of the above discussed analogue experiments. In most cases, surface and subsurface data provide sufficient control on the geometry of structures at the level of the Mesozoic sediments. However, interpretations at the basement level (undeformed or involved), are often more conjectural, particularly where surface

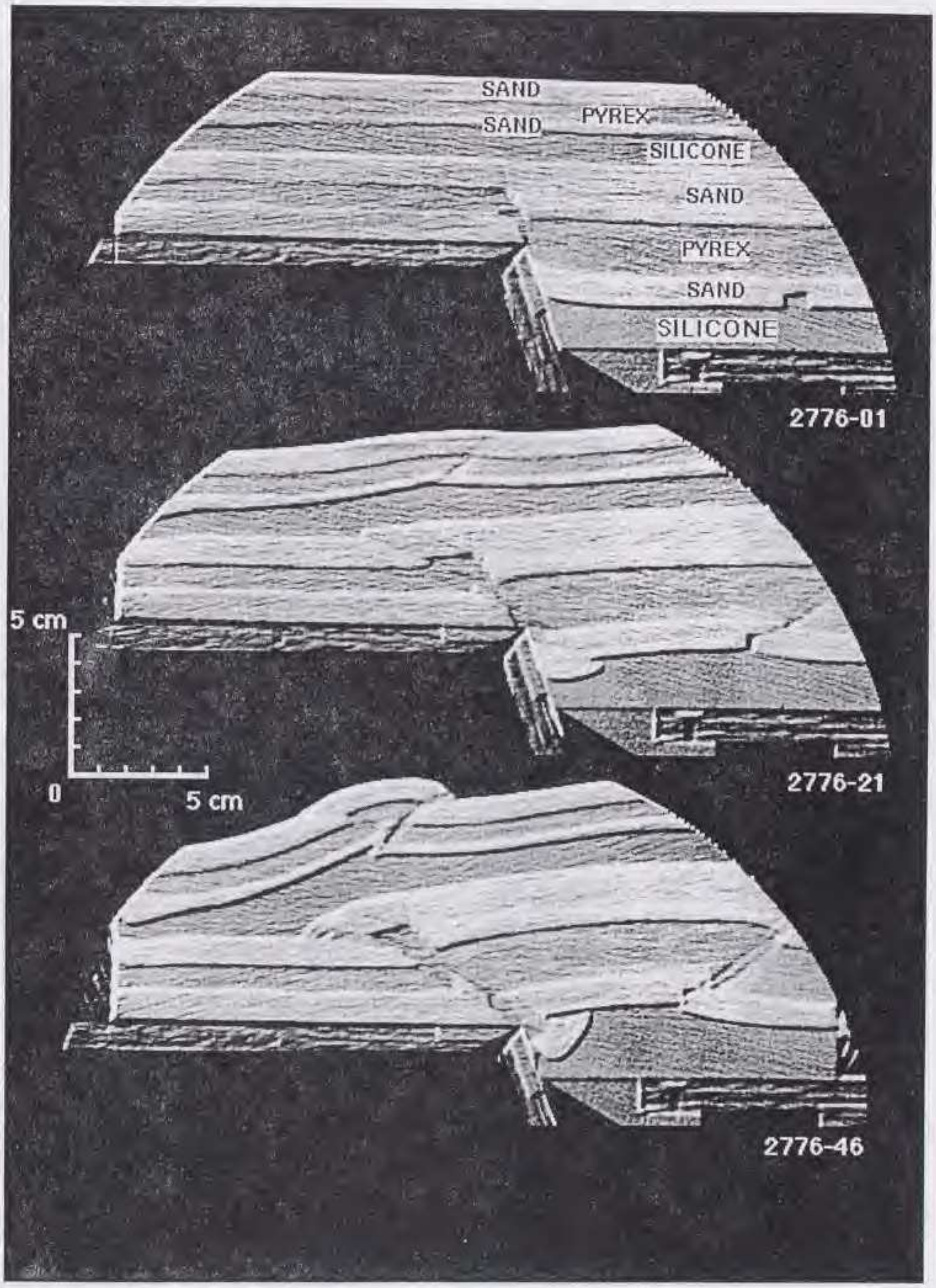

FIG. 6. Incremental deformation of a hangingwall block controlled by a planar basement fault, in a sand-box experiment simulating the tectonic inversion of a multilayer sand-silicone model. Note the short-cut in the basement, and wedging and backthrusting in the sedimentary cover.

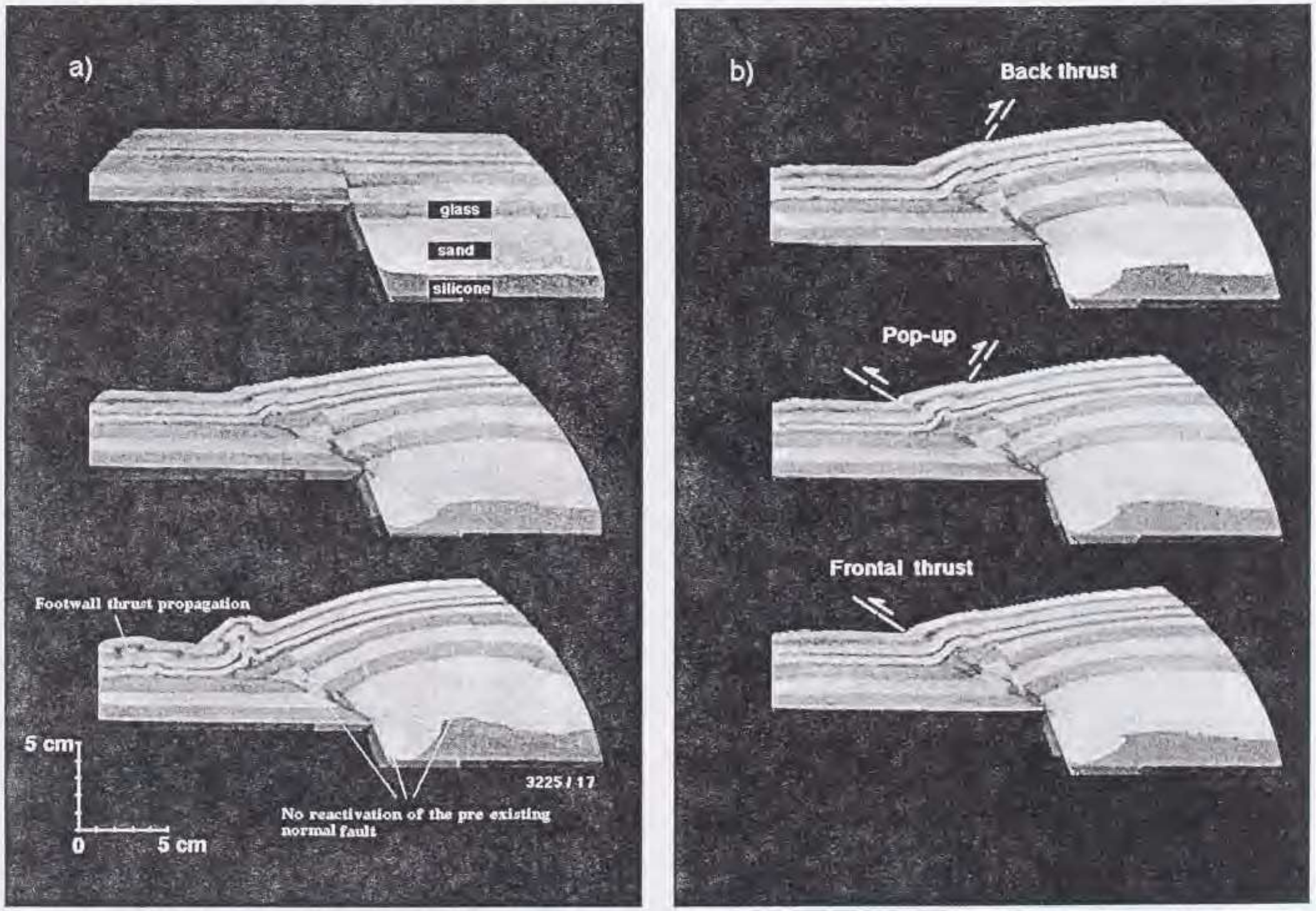

FIG. 7. a) Incremental deformation in a sand-box experiment simulating the tectonic inversion of a multilayer sand-silicone model, with reactivation of planar normal basement faults.
b) Serial cross sections of the deformed model showing the lateral changes from forward-directed thrusting to back-thrusting in the uppermost sedimentary cover, with the occurrence of a pop- up structure in the intermediate domain.

complexities prevented good reflection seismic resolution at depth.

As the major point of discussion concerns the relative allochthony or autochthony of the surface structures, we first tried to restore and balance the sections assuming a minimum amount of horizontal shortening (in-situ deformation above pre-existing basement structure). The subsequent comparisons with the models provided further insight into the coherency of the structural reconstruction, and brought a new approach to identify pre-existing basement structures and buried inverted Paleozoic basins at depth.

4.1 Pyrenean Inversion of Permian Basins

In the European foreland of Languedoc and Provence, several structures strike easterly; however, not all of them are of Pyrenean origin nor are they related to pre-existing Late Paleozoic structures. Some of them display Miocene (Alpine) deformation or are related to the reactivation of Jurassic (Tethyan) structures. This is the case for instance for the Alpilles, Ventoux-Lure and the Luberon massifs in Provence (Figs. 1, 9a and 13a).

Therefore, we have selected here only two structures, one in Languedoc (Pic-St. Loup), and the other one in Provence (Ste. Victoire), for which Pyrenean deformation is attested, and Late Hercynian inheritance can be documented with some confidence.

4.1.1 The Pic-St. Loup Triangle Structure in Languedoc

The Pic-St. Loup structure (Fig. 8) is an east-trending, north-verging asymmetric anticline, which is slightly thrusted over the syntectonic Eocene and Early Oligocene conglomerates of the St. Martin de Londres Basin (Figs. 1 and 8). In the west, the Pic-St.Loup structure is bounded by the northeast-trending Cévennes fault, a pre-existing Late Hercynian basement wrench fault, which was reactivated by left-lateral strike-slip motion during the Eocene deformation, synchronously with the development of the Pic-St. Loup structure (Arthaud and Mattauer, 1969). Eastwards however, the Pic-St. Loup overthrust is limited by the Corconne Fault, a younger, northeast-trending Oligocene normal fault, which is detached in the Triassic evaporites (Roure et al., 1988).

Regional geological studies and recently acquired reflection seismic data provide control on the shallow architecture of this structure. Only slight facies variations are recorded in the surrounding Upper Jurassic sequence, with shallower-water deposits being found south and west of the Pic-St. Loup than to its north and east (Dreyfus and Gottis, 1949). Similarly, bauxites developed in the south, whereas active subsidence still characterised the St. Martin de Londres Basin during the Cretaceous. Liassic platform carbonates outcrop in the core of the structure and were also penetrated by the Pic-St. Loup exploration well, thus implying a local basal detachment of the structure along Triassic evaporites.

Nearby exploration wells identified Permian sediments at depth to the north of the Pic-St. Loup; although these can be traced over a distance along seismic profiles (Roure et al., 1988), their presence is not confirmed south of the Pic-St. Loup. On a regional scale, the Permian strata presumably represent an eastwards extension of the Lodève Basin, which crops out west of the Cévennes Fault and is bordered into the south by the major north-dipping Montagne Noire high-angle basement fault (Figs. 1 and 8; Santouil, 1980). The eastwards extent of this basement fault cannot be confirmed on seismic lines, which are of poor quality beneath the steeply dipping Jurassic limestones of the Pic-St. Loup. Remote sensing studies, however, help to trace it beneath the Mesozoic sedimentary cover. On satellite images it appears as an east-trending lineament which extends beneath the Pic-St. Loup and crosses the Corconne Fault (Figs. 1 and 8; Chorowicz et al., 1991). The lateral offset of this Permian fault across the Cévennes Fault is the best argument for the Pyrenean reactivation of the latter.

Keeping these constraints in mind, a palinspastic restoration of a structural cross section across the Pic- St. Loup/St. Martin de Londres syncline was attempted. Among the various possible solutions (see Roure et al., 1994 for a discussion), the simplest one refers to an in-situ balance

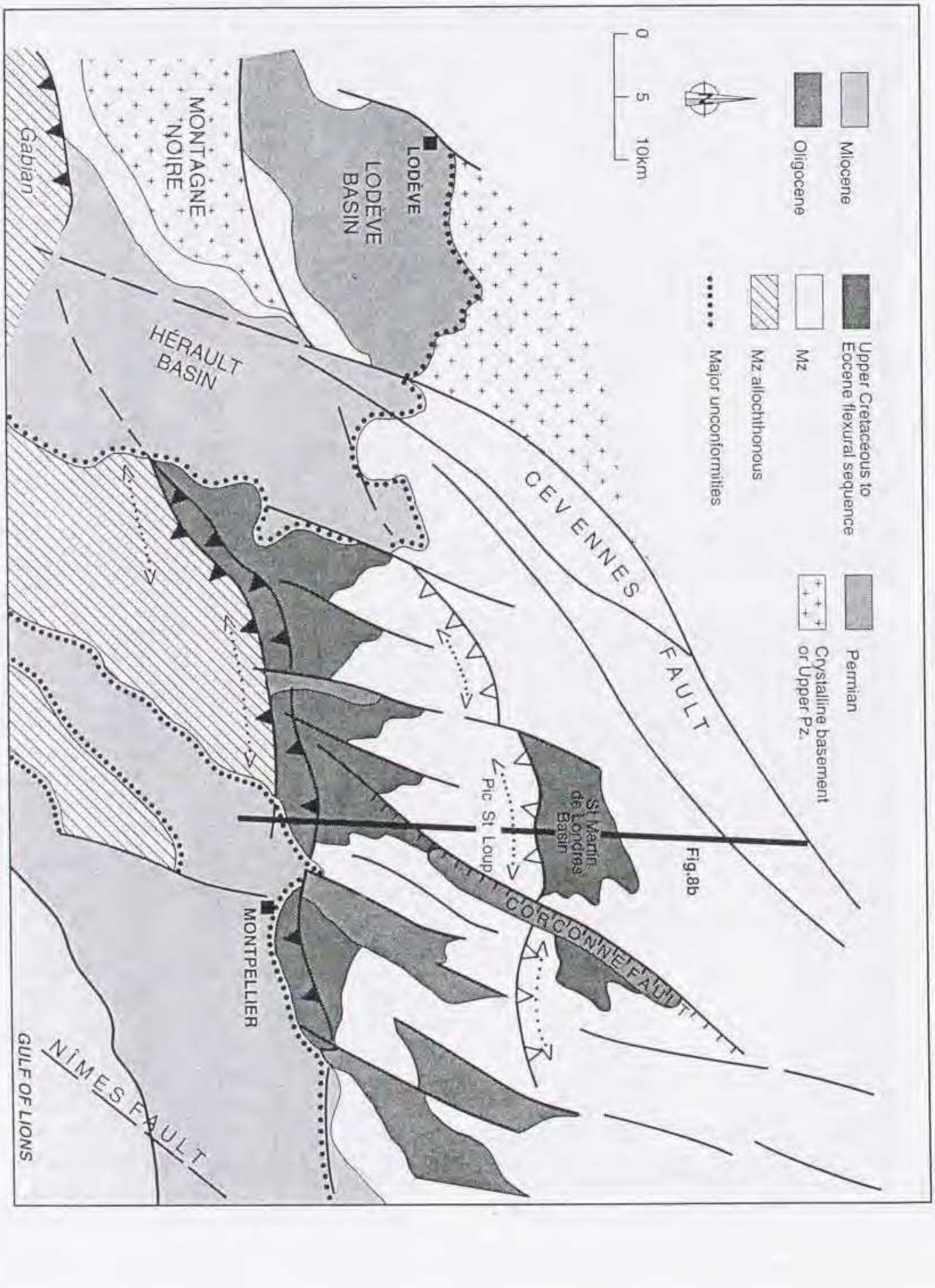

FIG. 8a. Structural map of the Pic-St. Loup / St. Martin de Londres area

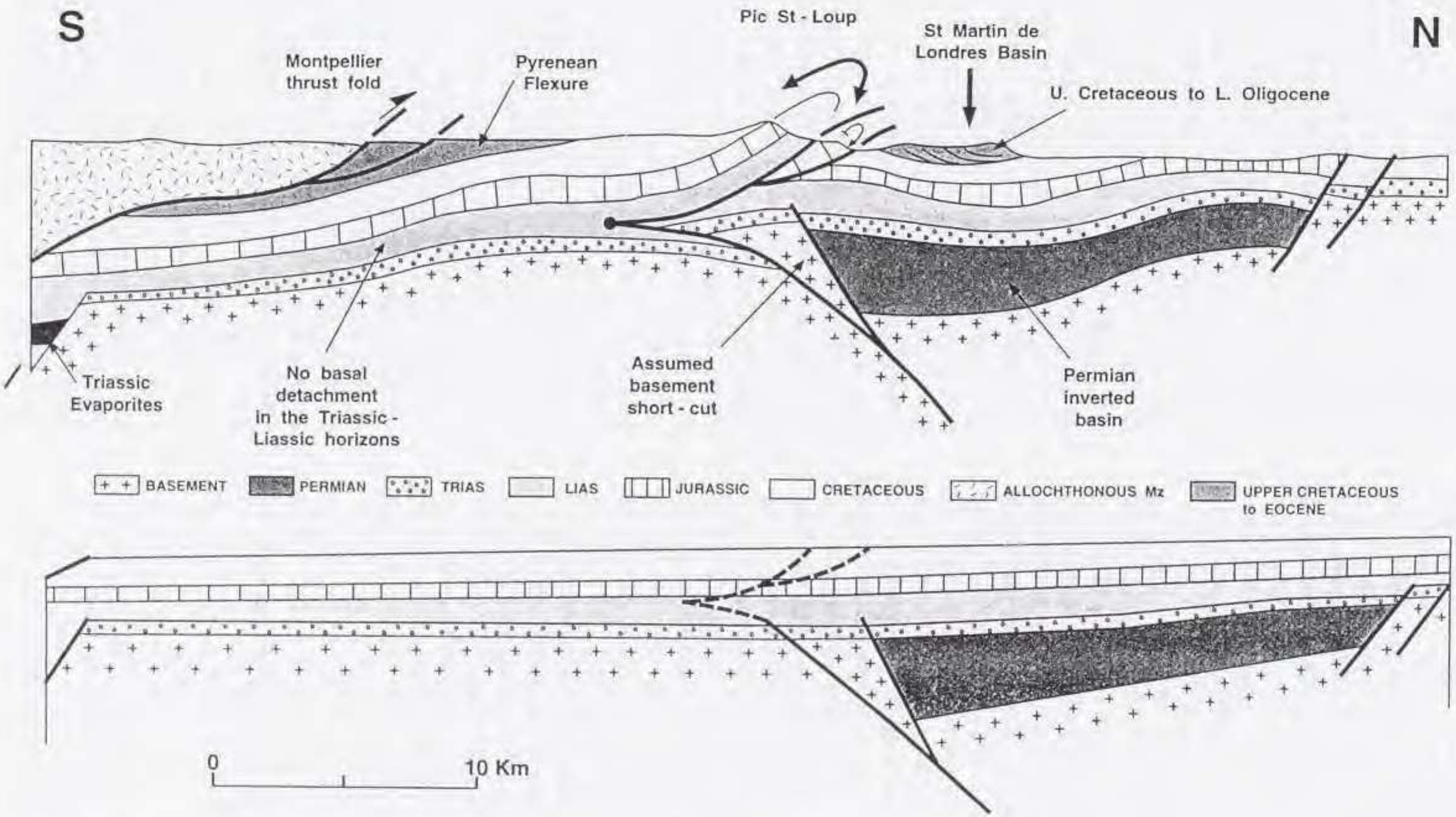

FIG. 8b. Structural and palinspastic sections of the Pic St. Loup structure in Languedoc. Note north-verging back-thrust in Mesozoic platform sequence over adjacent basin, due to the deeper inversion along a north-dipping basement border fault of a thick Permian basin.

between surficial shortening and basement reactivation (Fig. 8). As discussed earlier, the Pyrenean thrust front can be located with good confidence at the front of the Montpellier thrust, and there is no compelling evidence to postulate a continuous detachment of the sedimentary cover between Montpellier and St. Loup structures. Moreover, surface observations along the north-dipping Montagne Noire-Lodève Basin Permian border fault confirm that this structure was reactivated during the Pyrenean orogeny (Santouil, 1980).

A better understanding is obtained of the Pic-St.Loup structure, which is characterised by backthrusting in the sedimentary cover and basement inversion of the substratum, when compared with the analogue models (Fig. 6). In this case, the brittle platform domain in the south is progressively wedged out during the partial inversion of the Permian basin. The occurrence of shallow Triassic ductile layers at the base of the rigid Mesozoic carbonates permits their decoupling from deeper levels and the development of a conventional triangle zone. However, the poor quality of the reflection seismic data beneath the Pic-St. Loup structure does not provide any direct evidence for a low-angle short-cut in the basement, which would have to be assumed according to the sand-box models, if the maximum horizontal compressional stress trajectory was at a high-angle to the trend of the pre-existing normal fault during the inversion process (Figs. 6 and 7).

East of the Corconne Fault, a careful study of the architecture of surface structures also attests for a reactivation of the Permian structure. However, unlike in the Pic-St. Loup area, Mesozoic sediments are here involved in a south-verging overthrust (Fig. 8), which fits with the geometry of the pre-existing basement fault; this is a more common attitude for inverted structures.

4.1.2 The Sainte Victoire Pop-up Structure in Provence

The Ste. Victoire Massif (Fig. 9), an east-trending and about 1000 m high structure, is probably the most famous geological feature in Provence; however, its development is still the subject of controversy (Durand and Tempier, 1962; Corroy et al., 1964; Chorowicz and Ruiz, 1979; Durand and Gieu, 1980; Biberon, 1988). At the surface, the Ste. Victoire structure corresponds to a large anticline, cored by Jurassic platform limestones. In the west, it is thrusted to the south, and overlies thick Late Cretaceous synkinematic proximal breccias, as well as the Late Cretaceous to Eocene synflexural continental sediments of the Arc syncline (Figs. 1 and 9). In the east, the Ste. Victoire Massif gradually acquires a north-verging attitude; its central portions constitute a pop-up structure.

Geophysical data confirm a southwards deepening of the basement, from a 3 km depth north of the Ste. Victoire Massif, down to 4 km beneath the Arc syncline (Biberon, 1988); however, reflection seismic do not allow to determine whether the basement is faulted or only gently flexed beneath the Ste. Victoire anticline. Triassic and Jurassic sequences display no significant lateral thickness change and thus, preclude Mesozoic faulting. On the other hand, more than 1 km thick Permian strata occur along the eastern margin of the Arc syncline, whereas to the north of the Ste. Victoire structure, Triassic strata rest directly on basement; this is taken as indirect evidence for Permian faulting beneath the Ste. Victoire structure.

Within the predominantly brittle Permian and Mesozoic clastic and carbonate strata, Triassic evaporites and Upper Jurassic (Oxfordian) black-shales provide potential décollement levels. In view of the omnipresence of Triassic evaporites, many authors consider the Ste. Victoire structure and even northwards adjacent folds and thrusts as thin-skinned features forming part of the Pyrenean orogenic front (Tempier, 1987; Biberon, 1988).

Alternatively, and keeping the results of sand-box simulations of basement-controlled inversions in mind, most the Ste. Victoire structure can be balanced in situ, assuming it is superimposed on a south-dipping Permian high-angle fault controlling the distribution of Late Paleozoic strata beneath the Arc syncline.

Therefore, it is proposed that structural inversion of the Arc Permian basin induced wedging in the Mesozoic sequence, involving its detachment along intra-Triassic and Oxfordian ductile levels as evident by rapid lateral changes in attitude of surficial thrusts. Scale-down models of tectonic inversion in multilayer sand-cakes illustrate the development of similar pop-up structures in transition zones, with mass transport evolving from out of the basin (forward) to into the basin (backthrusting) (Figs. 6 and 7).

In the case of the Ste. Victoire structure, the amount and location of erosion during and after an initial episode of gentle deformation (i.e. Late Albian-Early Cenomanian, or Maastrichtian to Montian; Durand and Tempier, 1962) probably modified the geometry of the hanging-wall, inducing lateral changes in the boundary conditions, which localised the change from backthrusting to frontal deformation during the Eocene episode of main inversion (Lutaud, 1935, 1957). Also in this case, the postulated occurrence of a low-angle basement short-cut beneath the Ste. Victoire structure remains hypothetical for lack of subsurface control.

In our interpretation, most, if not all, of the shallow deformation observed in the Ste. Victoire structure can be balanced in situ by an equal amount of basement shortening (Fig. 9b). However, a minor northwards translation of the entire Arc syncline above an intra- Triassic detachment cannot be precluded. In this second hypothesis, the role of the basement fault would be to localise the Pyrenean deformation of the detached Mesozoic sediments.

4.2 Alpine Inversion of Late Paleozoic Basins (Subthrust High Jura Architecture)

Also in the Jura Mountains, the incidence of pre-existing Paleozoic features on Cenozoic compressional structures is evidenced, where boreholes and reflection seismic profiles have identified Late Paleozoic basins, deeply buried beneath the allochthonous Mesozoic cover (Laubscher, 1986; Noack, 1989).

The ECORS deep seismic profile and recent petroleum exploration data permit a correlation between the occurrence of basement-controlled inversions at depth, and the abnormally high topographic elevation of the inner parts of the Jura Mountains (i.e. the Grand Cret d'Eau, 1600m high; Guellec et al., 1990b; Roure et al., 1990, 1994; Philippe, 1994), as compared with the low relief of the Molasse Basin to the Southeast (average 500 m), and of the Bresse Basin in the northwest (average 250 m) (Figs. 1, 3 and 10).

Figure 10 gives a structural cross section through the High Jura Mountains, that is based on surface and subsurface data. A recently drilled well (Charmont) demonstrates the occurrence of thick Permo-Carboniferous sediments beneath the deformed Mesozoic strata of the Jura Mountains, which are detached from their substratum at the level of the Triassic evaporites. In the direction of mean transport, the detachment plane rises from the Molasse Basin into the High Jura Mountains and plunges again at their outer margin.

Backthrusting occurs in the Mesozoic series at the western border of this anomalous subthrust configuration (Oyonnax backthrust), and can be attributed to deformation of the Paleozoic substrate and basement. The observed geometric relationships between the Mesozoic allochthon and its substrate suggests inversion of the Permo-Carboniferous basin occurred after the westwards translation of the Mesozoic series, resulting in deformation of the intra-Triassic detachment horizon. Eventually, the west-verging overthrust of the Grand Cret d'Eau structure, along the southeastern margin of the Jura Mountains, can be interpreted as an out-of-sequence reactivated thrust, that formed during the inversion of the Permo-Carboniferous trough. It is proposed that the recent basement-involving shortening, causing deformations of the allochthon, should be locally balanced, rather than involving reactivation of the entire Jura allochthonous and mass-transport in the opposite directions, i.e. to the west near Oyonnax, and to the south-east beneath the Molasse Basin.

Again, sand-box models of basin inversion (Figs. 6 and 7) provide a rational for proposing coherent scenarios for the development of such triangle zones, with basement inversion at depth, and synchronous conjugate backthrusting in the sedimentary cover. However, it is proposed that the structure of the High Jura Mountains results from a 2-phase deformation:

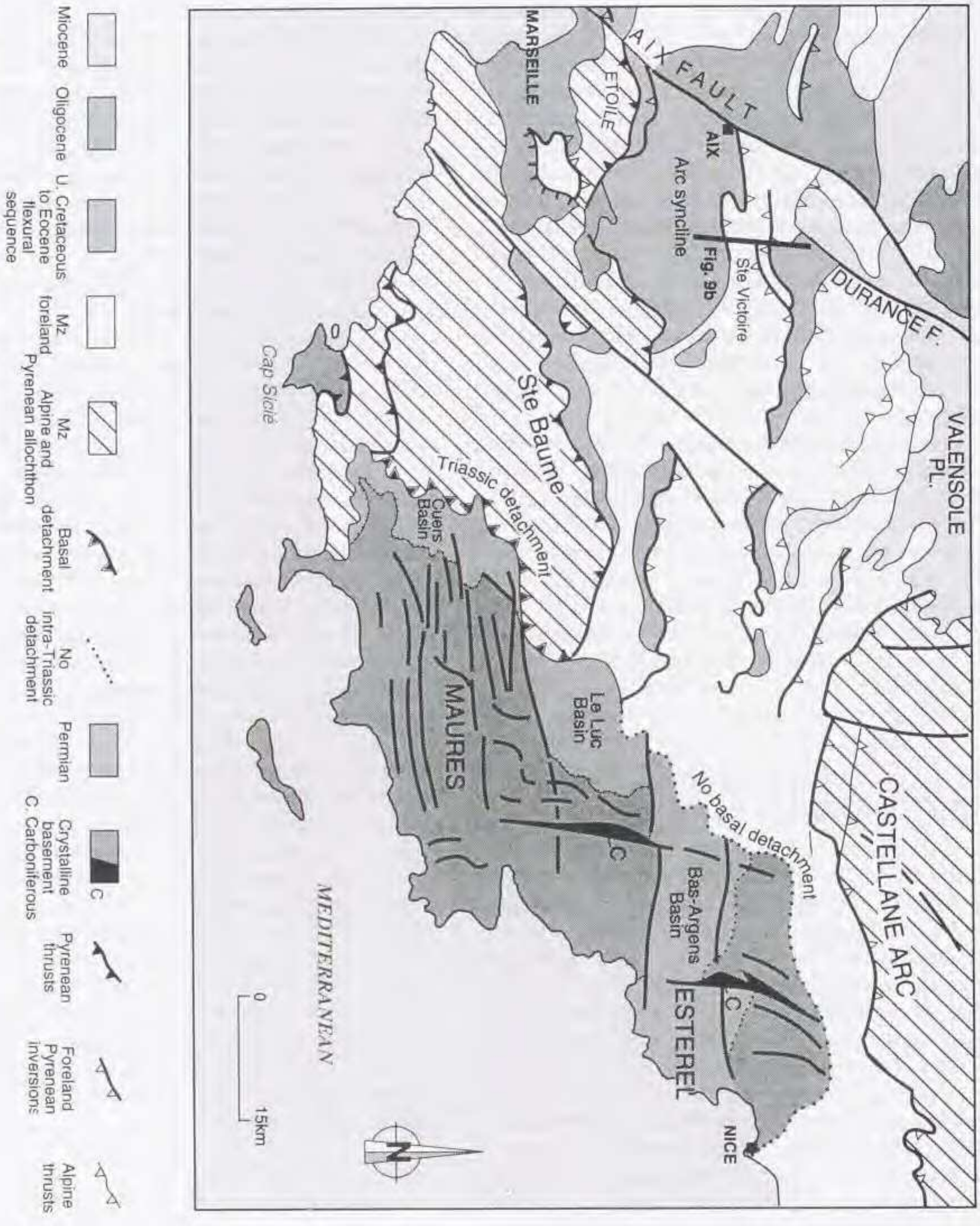

FIG. 9a. Structural map of the Ste. Victoire / Arc syncline area.

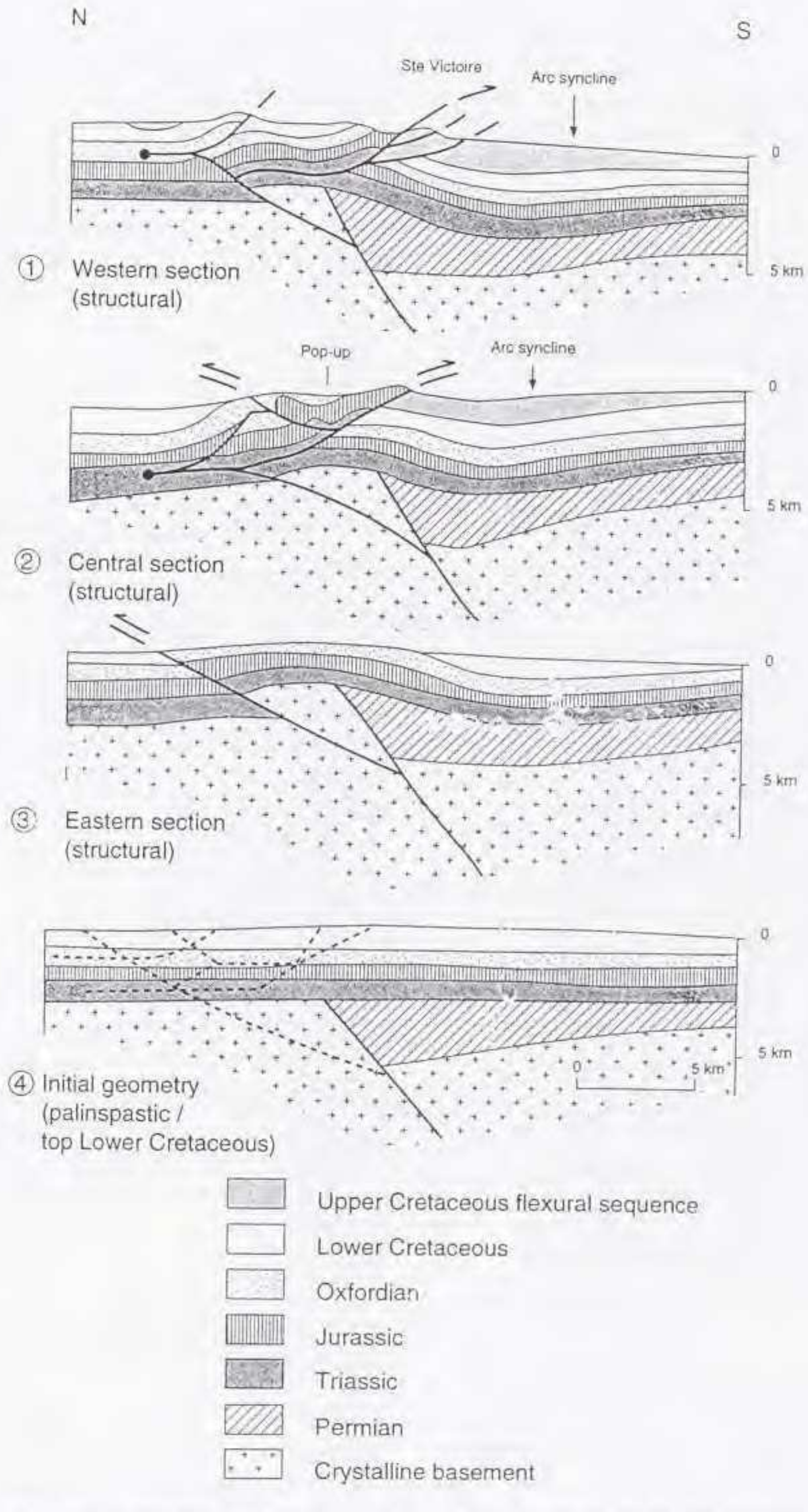

FIG. 9b. Structural and palinspastic serial cross sections of the Ste Victoire structure in Provence.

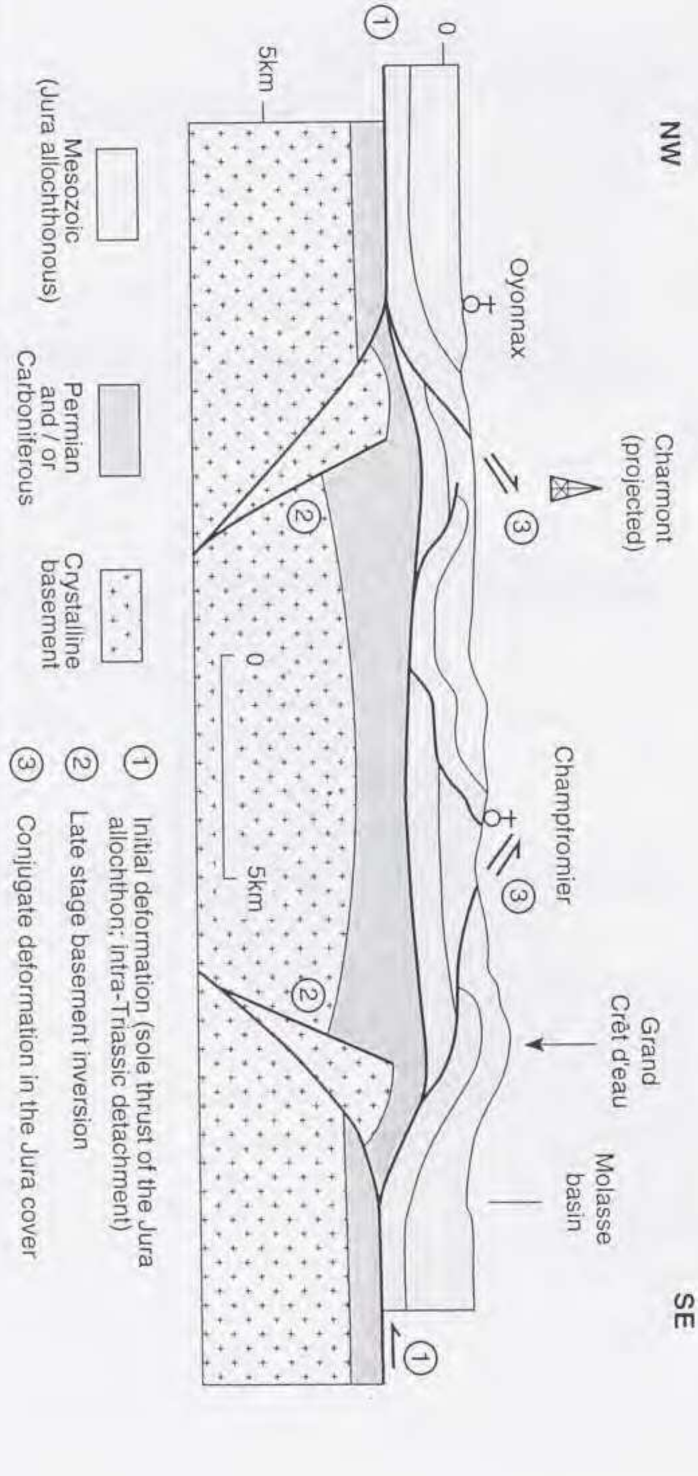

FIG. 10. Subthrust inversion of Late Paleozoic basins beneath the High Jura Mountains (modified from Philippe, 1994).

(1) west-verging detachment folding and thrusting of the Mesozoic sediments during the Miocene deformation phase which stopped during the Pontian (Jura thrust-emplacement over the Bresse Graben).
(2) subthrust basement-involving inversion of Permo-Carboniferous basins, development of the Oyonnax backthrust and reactivation of the Cret d'Eau structure between the Pontian and Present.

5 TETHYAN INHERITANCE AND CENOZOIC INVERSIONS

The role of pre-existing Tethyan rifting on subsequent Alpine deformations is well known in the sub-Alpine or External Crystalline Massifs of the Western Alps (Gillcrist et al., 1987; Mugnier et al., 1987; Graciansky et al., 1988; Gratier et al., 1989; Guellec et al., 1990a, 1990b). However, large amounts of shortening and the frequent complete allochthony of these reactivated structures prevents accurate reconstruction of their initial configuration (i.e. basement-cover relationships). The study of Alpine inversion features in the European foreland, away from the major Alpine thrust front, is facilitated by the quality of the reflection seismic profiles which usually increases towards the autochthon; moreover, reduced amounts of shortening provide better conditions there for studying the geometry of both the basement and the involved sediments.

5.1 Basement Control on Deformation (the Durance Fault)

The Durance Fault is generally regarded as a Late Hercynian structures, due to its northeast strike (Arthaud and Matte, 1975). However, geological and geophysical data permit only to evaluate its Mesozoic and Cenozoic history.

Surface geology, exploration wells and recent reflection seismic surveys provide constraints on regional structural cross sections across the Durance Fault:

(1) east of the fault, the Valensole Plateau is characterised by a reduced Mesozoic platform sequence (Dubois and Curnelle; 1978), which is still attached to its basement due to the lack of Triassic evaporites. In most places, the Cretaceous sequence has been entirely eroded and marine to continental Miocene sediments rest disconformably on Jurassic carbonates (Fig. 11).
(2) a second extensional phase occurred during Late Aptian to Cenomanian times, giving rise to the development of horsts-and-grabens on, the hanging-wall. During the Late Senonian-Eocene Pyrenean the hanging-wall basin was partly inverted and the resulting topography eroded. During Oligocene times the tensional Manosque basin developed. During the Miocene, this basin was incorporated into the Valensole basin. During the Late Miocene to Present, the Manosque basin was inverted in response to Alpine compressional stresses (Fig. 11b).
(3) the Durance Fault clearly involves the basement, but part of its successive vertical or oblique motions were balanced in the foot-wall by lateral escape of the Mesozoic series along a basal intra-Triassic décollement. As a result, the deep architecture of the fault comprises two complementary features: a listric normal fault, flattening in the Triassic and a high-angle fault, rooting in the upper crust.

The Oligocene infill of the Manosque Basin is presently involved in a complex anticlinorium, partially transported towards the east, the culmination of which is located at a higher elevation than the Miocene molasse of the Valensole Plateau in the hanging-wall; this attests for a Neogene, Alpine, inversion episode (Fig. 11b). When restoring the

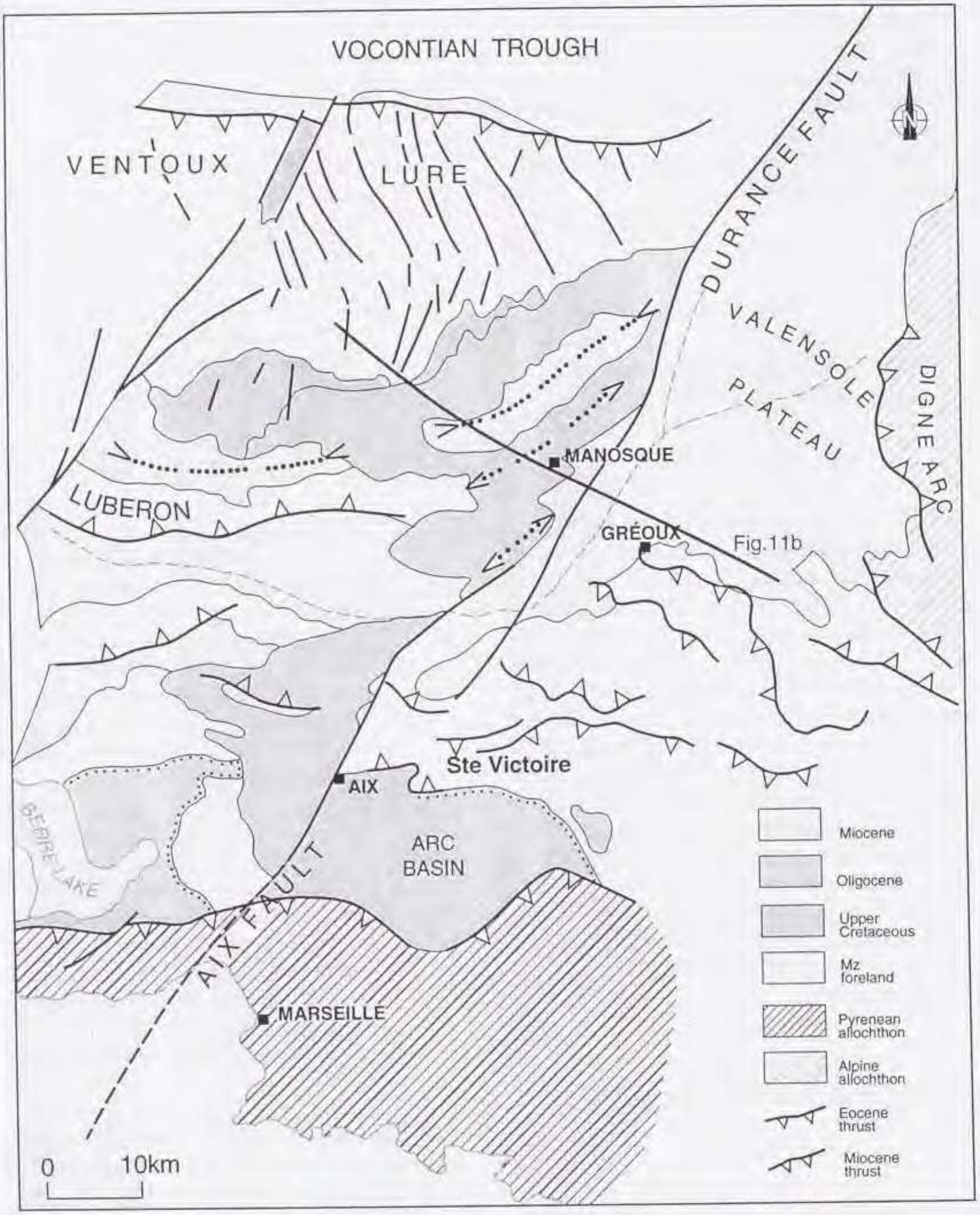

FIG. 11a. Structural map of the Durance Fault / Manosque area

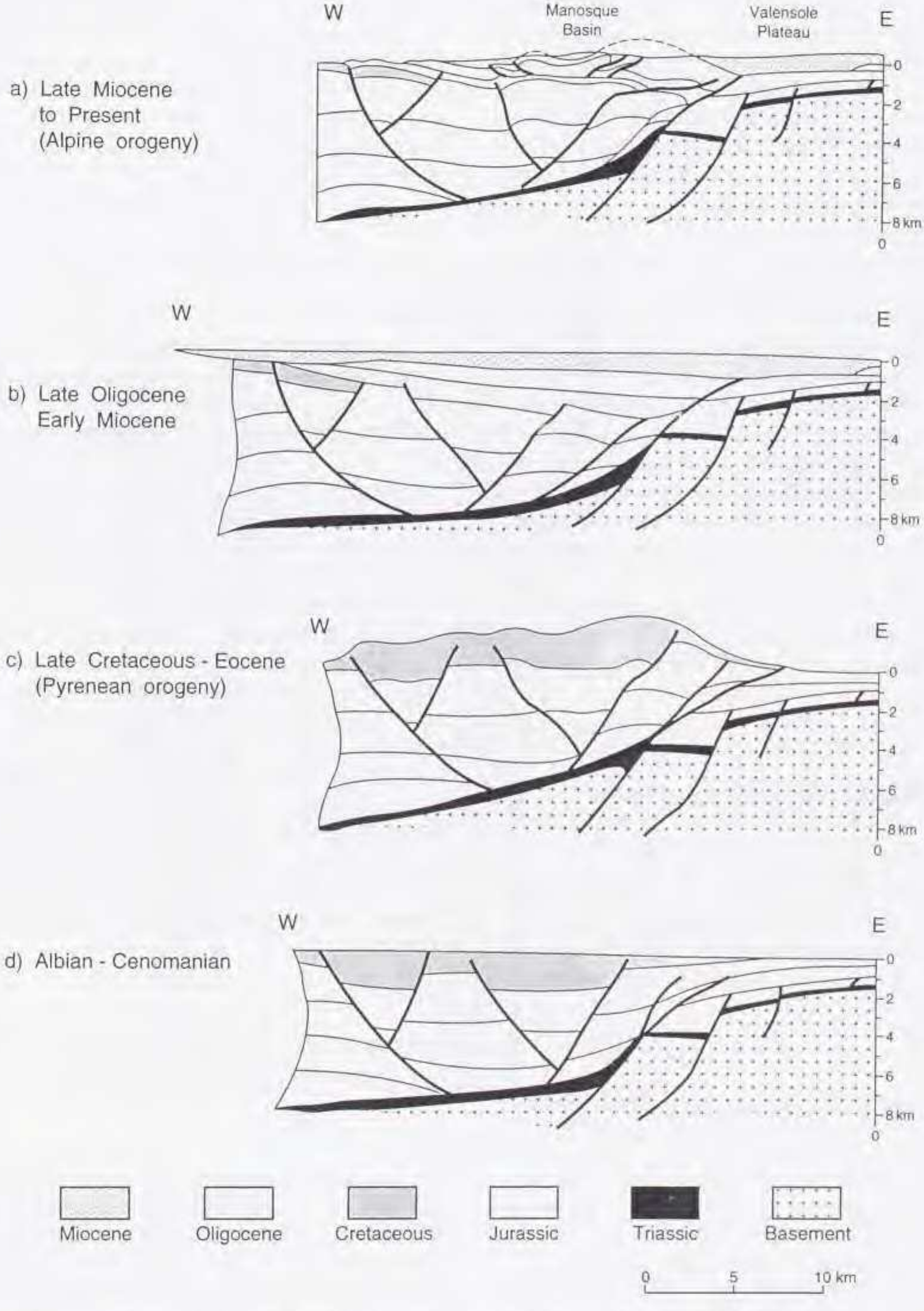

FIG. 11b. Structural and palinspastic sections along the Durance Fault, outlining the Alpine structural inversion of the Manosque Oligocene basin.

section to its pre-Oligocene geometry, the distribution of Albian-Cenomanian series is very peculiar; Lower Cretaceous horizons are only preserved in distal portions of the foot-wall. This is interpreted as evidence of post-Cenomanian erosion, resulting from an earlier episode of tectonic inversion, occurring after the Lower Cretaceous and prior to the Oligocene, presumably during the Late Cretaceous-Eocene Pyrenean orogeny.

By comparing the geological cross-section and its palinspastic restoration with analogue models for compressional/transpressional reactivation of a listric normal fault (Figs. 5 and 11), a better understanding is obtained of the internal deformation of the Oligocene Manosque Basin. Its antiform geometry is controlled by a set of conjugate thrust faults, which are rooted in an intra-Oligocene salt horizon (Fig. 11). When restored to a pre-Alpine geometry, these faults root in the vicinity of Cretaceous grabens, which developed in the crestal part of a regional roll-over structure. As observed by X-ray tomography during incremental deformations of a sand-cake, the localisation of the shallow thrusts is controlled by the pre-existing high-angle tensional faults of the roll-over structure (Roure et al., 1992; Fig. 5).

5.2 Sedimentary Control of Deformation

Apart from the configuration of the basement, lateral thickness and facies changes of the sedimentary cover can control the localisation of inversion deformations. Two examples are discussed below.

5.2.1 Inversion of the Terres Noires Shale Basin

Figure 12 gives a regional structural cross-section and its palinspastic restoration through the Alpine Vercors thrust front and the Eastwards adjacent inverted "Terres Noires" shales basin (for location see Figs 1 and 13). This is one of the best examples to demonstrate the control of thickness and lithofacies changes on the structural style of a compressionally deformed sedimentary package.

From east to west, the thickness of the deformed Mesozoic sequence decreases from more than 8 km in the Vocontian Trough to less than 4 km beneath the Rhône Valley, in the footwall of the Cévennes Fault. Deformation of this basin involved the activation of a sole thrust which ramps up from an intra-Triassic salt layer through Early Liassic carbonates into the Liassic Terres Noires shales and ultimately through the Middle and Late Jurassic carbonates into basal Cretaceous shales.

At the same time, the intra-Triassic detachment constitutes the sole-thrust during the Alpine basin inversion in the east, whereas the Liassic platform carbonates of the external domain are still preserved in the foot-wall beneath the Vercors overthrust. There, two additional shale horizons in the Jurassic (above the Liassic carbonate) and the Neocomian (beneath the Aptian Urgonian Formation), allow for the detachment of the more rigid, mainly brittle platform areas.

The topographic culmination of the inverted "Terres Noires" basin at Aurel is located above the place where the basal detachment ramps up from an intra-Triassic to an intra-Liassic level, and thus corresponds to a ramp anticline involving the entire shale basin. As imaged in the analogue models, a triangle zone develops at the front of the inverted structure; beneath the Rhône Valley, the brittle Urgonian platform carbonates are progressively detached above the Neocomian shales, and thrusted backwards over the basinal allochthon (Fig. 12).

5.2.2 Inversion at Urgonian platform margin (La Lance and Ventoux structures)

La Lance and Ventoux-Lure overthrusts, which strike northwest and east, respectively, are located along the shale-out edge of the Aptian carbonate shelf (Urgonian Formation) of the Provence platform. These structures are thrusted northwards or northeastwards over the margins of the "Terres Noires" shales basin corresponding to the Vocontian Trough (Villéger and Andrieux, 1987; Ford,

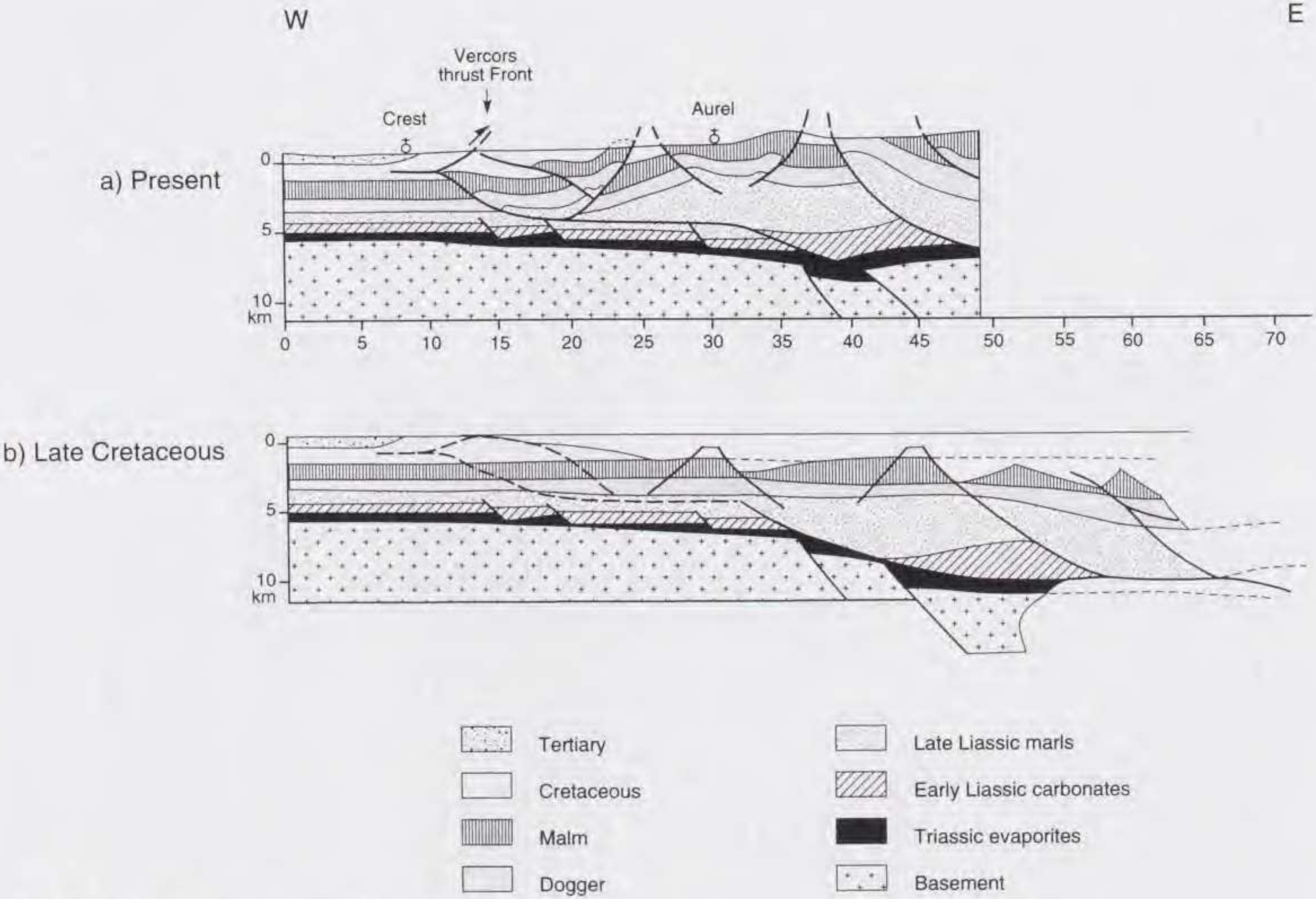

FIG. 12. East-west srtructural and palinspastic sections across the Vercors overthrust parallel to the Drôme River. See location of the section on Fig. 13a.

1993; Ford and Stahel, 1995; Figs. 1 and 13), and form two distinct and isolated culminations near the Rhône Valley; these are located far away from the Alpine thrust front. The highest peak of the Ventoux-Lure trend has an elevation of 1912 m and is referred to as the Giant of the Provence.

Reflection seismic profiles provide control on a major basement involving normal fault beneath La Lance structure, and associated changes in thickness of the Mesozoic sediments (Fig. 13b). The Jurassic sequence is thicker in the north ("Terres Noires"), whereas the Urgonian platform, quite thick beneath the autochthonous Valreas Basin, displays classical northwards progradations (Figs. 2 and 13b). Structurally speaking, the top of the Jurassic sequence culminates in the north in the area of the inverted basin, presently at 1800 m above its position in the stable Valreas Basin platform. This is clearly the result of a post-Cretaceous structural inversion. A minor complicating factor are Triassic evaporite diapirs, which are associated with basement faults, as evident on seismic data near Dieulefit beneath La Lance overthrust (Fig. 13b; Dardeau et al., 1990).

Paleogene and marine Miocene molasse is only preserved in the Valreas Basin, where it rests concordantly on Mesozoic strata. The structural conformity between Miocene and Mesozoic strata on the back-slope of the La Lance structure is the best constraint on its Alpine deformation.

Apart from the basement-involving high-angle fault and the intra-Triassic décollement level observed in the foot-wall of the structure, two additional detachment horizons are evident on seismic records (Figs. 2 and 13b; Roure et al., 1994), namely:

(1) Jurassic shales above the Liassic carbonates in the southern platform domain, in the hanging-wall beneath the Valreas Basin,
(2) and a Neocomian to Aptian shaly sequence in the basinal domain, which constitutes a ductile counterpart (lateral facies transition) for the brittle Urgonian carbonates.

However, similarly to the La Lance structure, it is assumed that the Ventoux Lure and Luberon thrusts are superimposed on deep seated basement faults which were actives during Triassic and Jurassic times (Fig. 13c). Observed thickness changes in the Urgonian platform carbonates are related to differential compaction of the Terres Noires shales over which these carbonates prograded.

As in some analogue experiments, the tectonic inversion of the Vocontian Basin has led to a progressive backthrusting of the platform domain over the thick shale basin. This wedging, and related development of a triangle zone, is indeed mainly controlled by the rheological contrast between the brittle Urgonian carbonate platform and the more plastic shaley basinal sequences; it is, however, greatly facilitated by the occurrence of secondary intra-platform décollement levels.

6 ALPINE INVERSION OF OLIGOCENE STRUCTURES

The latest Miocene episode of oblique inversion recorded along the Durance Fault is the best evidence for Alpine compressional reactivation of Oligocene extensional structures. It resulted in intense folding and thrusting in the Paleogene sequences of the Manosque basin (Fig.11; Roure et al., 1992).

Less obvious Miocene compressional deformations and fault reactivations have been locally described along the Cévennes Fault and in the Oligocene fill of the Alès Basin, west of the Rhône Valley (Fig. 1).

Surprisingly, however, large portions of the so-called West European Rift system were preserved from any direct reactivation during the Neogene, even close to the Alpine front. For instance, the Oligocene and Miocene fill of the Bresse Graben was partly overridden during the Pontian (Mio-Pliocene boundary) by the Jura allochthon; however, no major Oligocene faults appear to have been reactivated at that time within this basin (Mugnier and Viallon, 1984; Bergerat et al., 1990; Guellec et al., 1990a, 1990b; Fig. 3c).

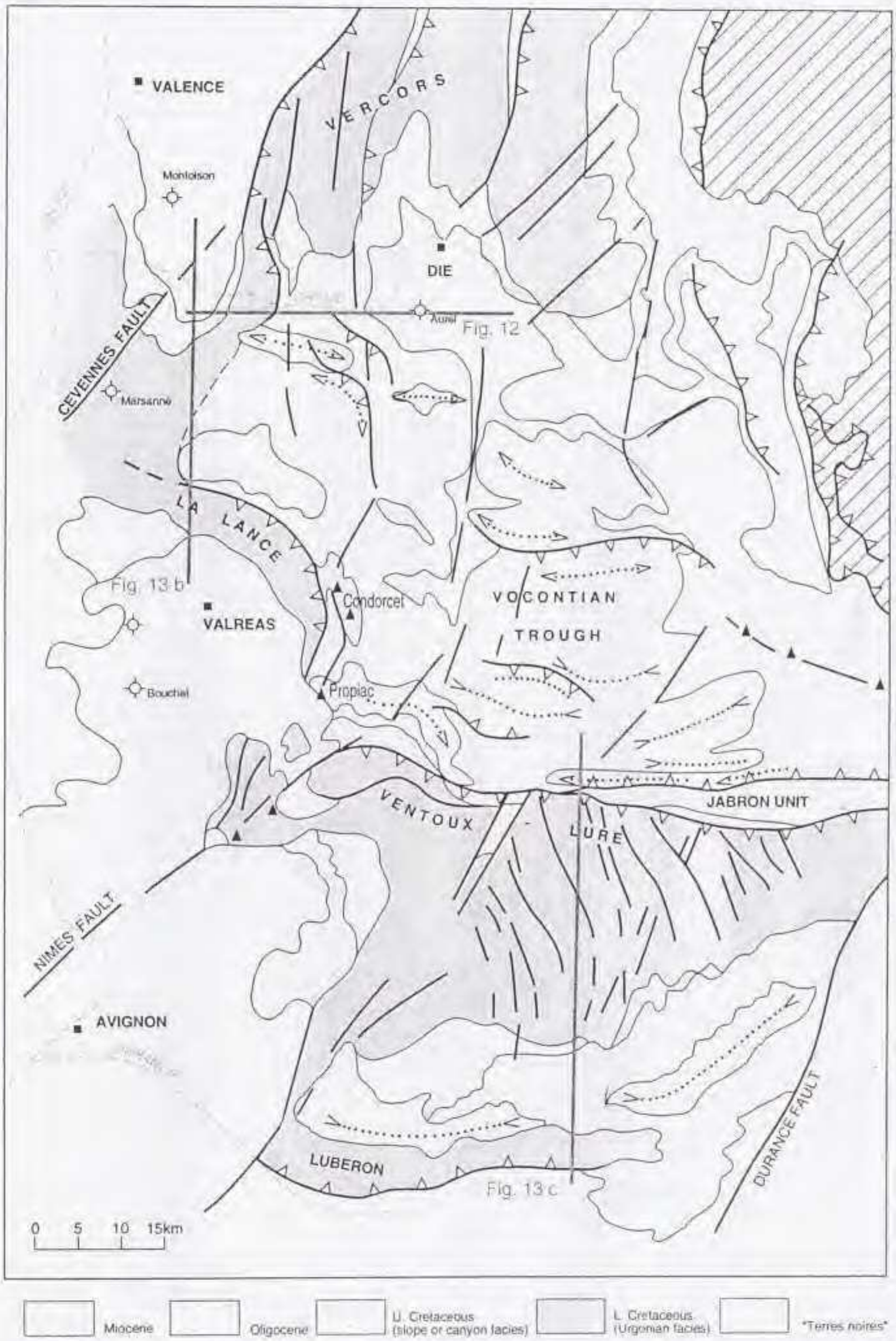

FIG. 13a. Structural map of La Lance / Ventoux-Lure area

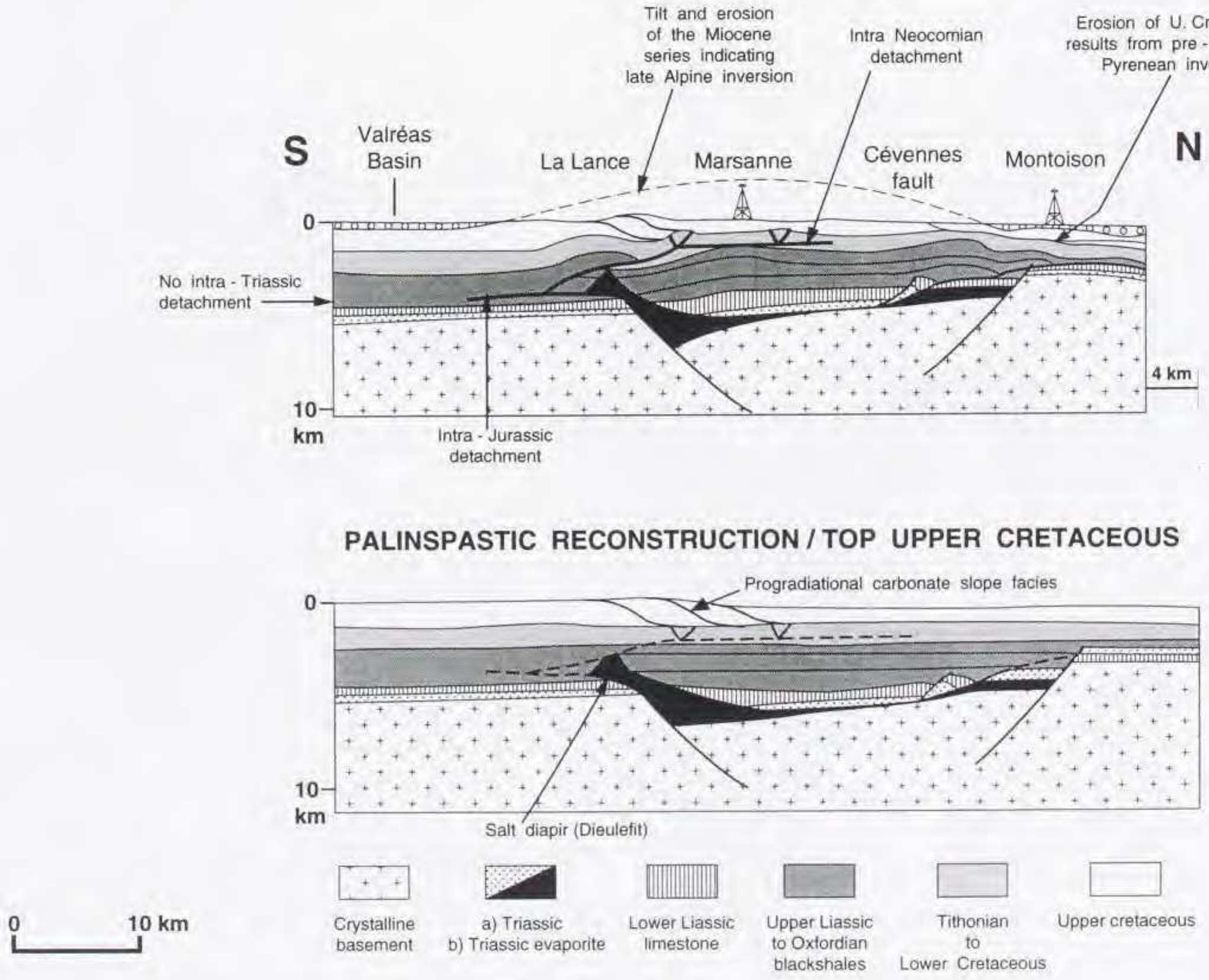

FIG. 13b. Structural and palinspastic sections across La Lance overthrust.

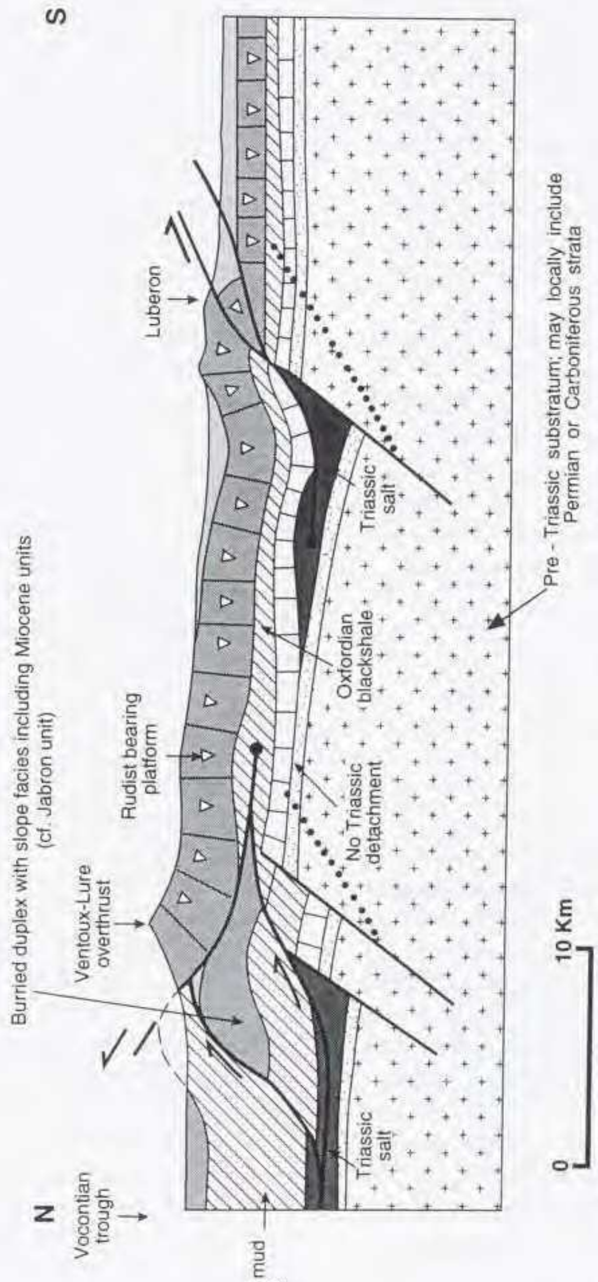

FIG. 13c. Structural and palinspastic sections across Ventoux-Lure overthrust.

Nevertheless, detailed microtectonic analyses outline the effects of the Alpine compression all over the European foreland, especially near the Jura front in the Bourgogne area (Bergerat, 1985; Lacombe et al., 1990). The important uplift and erosion observed in the southern part of the Rhine Graben, as imaged by longitudinal cross-sections of the graben (Sittler, 1965), could eventually account for Late Miocene inversion. Moreover recent strike-slip movements have been recognised on several faults of the Vosges Massif (Villemin and Bergerat, 1987), and a strike-slip mechanism is indicated by earthquakes in the southern part of the Rhine Graben (Bonjer et al., 1984).

Cenozoic foreland inversions are effectively also widespread further in the north, away from the Pyrenean and Alpine fronts, and have been described in the British Channel (Gillcrist et al., 1987), in the North Sea (Glennie and Boegner, 1981; Badley et al., 1989; Huyghe and Mugnier, 1994) as well as in Northern Germany and Poland (Ziegler, 1983, 1989, 1990 and references therein).

7 CONCLUSIONS

Tectonic inversion of pre-existing basement structures is the main mechanism which accounts for the structural complexity of the European foreland in Languedoc and Provence, north and west of the Pyrenean and Alpine thrust fronts, respectively. There, the competition between foreland basin inversions, resulting in localised uplifts, and low flexural subsidence of a thick lithosphere, prevented the development of large Late Cretaceous to Eocene and Miocene flexural foreland basins. Remnants of such basins are confined to relatively small depressions bordering the poorly expressed Pyrenean and Alpine frontal thin-skinned structures (St. Chinian, Montpellier fold, Arc syncline or Valensole Plateau). Oligocene rifting and subsequent thermal subsidence, linked to the development of the Gulf of Lions, provided additional complexities, and prevent any direct structural continuity between Languedoc and Provence compressional structures.

These compressional foreland deformations imply that the European plate as a whole was not rigid during the Pyrenean and Alpine deformations. Instead, the observed basement-involving within-plate deformations account for a progressive activation of very deep detachment levels within the continental lithosphere (presumably within the ductile lower crust), away from the recognised plate boundaries (Ziegler, 1983, 1989; Gillcrist et al., 1987;Roure et al., 1990; 1994).

However, the comparison of surface and subsurface data with sand-box experiments permits us to propose coherent structural interpretations at depth, and thus to link the major shallow complexities observed in the sedimentary cover with high-angle border faults delimiting Permian basins, and in some cases with Mesozoic or Oligocene extensional faults. Nevertheless, unlike in sand-box experiments or numerical models of tectonic inversion (Huygue and Mugnier, 1992; Vially et al., 1994), no clear basement short-cuts could be identified near the edges of reactivated normal faults. This may be due to poor resolution of the reflection seismic data beneath the inverted anticline structures (i.e. Pic-St. Loup and Ste. Victoire frontal structures, in which short-cuts could be expected), or an even greater importance of oblique mass transport than assumed (i.e. in La Lance or Durance). In this context, it is important to note that models predict that oblique compression facilitates the reactivation of pre-existing faults, precluding the development of basement short-cuts.

Due to the coexistence of a large set of trends, and due to progressive stress rotation during Late Cretaceous to Present times, the timing and mode of inversions was different for east-, north- or even northeast-trending structures. Orthogonal and oblique inversions thus coexisted at a regional scale, and multiphase deformations are recognised along a number of basement structures such as the Durance and Cévennes faults.

These new structural concepts may find application in the exploration for hydrocarbon. Most Late Paleozoic basins of southeastern France have a source potential for oil, as indicated by oil recoveries in Languedoc (Gabian trend beneath the intra-Triassic detachment; Barrabé and Schneegans, 1935), or recent oil shows in the subthrust Jura autochthon (Deville et al., 1994). Old mining industry cores also give evidence for the presence of mature source-rocks in the Paleozoic basins of Provence. Moreover, the recent discovery of oil in good quality Triassic reservoirs along the western border fault of the BSEF in the Ardèche (Morte-Mérie GPF scientific well; LeStrat et al., 1994), is apparently related to rich Permian source-rocks.

The structural complexity of the area presents a major exploration risk, particularly since prospects are mainly related to reservoirs located beneath the Triassic detachment surface. Maximum burial was generally reached prior to the inversion episodes; this would favour an initial migration of the hydrocarbon towards early extensional structures (Roure et al., 1994; Guilhaumou et al., 1995). However, inversion induced destruction of pre-existing hydrocarbon accumulations and the re-migration of oil and gas into newly developed structures, or their escape to surface, are further risk factors.

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